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Energy Conservation in Investment Casting Moulds using Canadian Industrial Materials

Phase II

Final Report

Energy Conservation in Investment Casting Moulds Using Canadian Industrial Minerals

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Phase II

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Treasurer & Controller

DESIGNED PRECISION CASTINGS INC.

122 pp

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In close consultation and full concurrence
with the writer and
the professional and technical staff of
Designed Precision Castings Inc.,
Lydia Luckevich, Research Scientist,
for our sub-contractor,
Ontario Research Foundation,
has compiled the attached final report,
which is respectfully submitted.

K. R. Heath
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DPC LOW FIRED MOULDS

PHASE II

Final Report No. 62-10503

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Period Covered: November 1, 1985 - March 31, 1987

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EXECUTIVE SUMMARY

This project was initiated to develop low-firing ceramic moulds for the investment casting industry. These moulds would conserve energy in the casting process by requiring lower firing temperatures than conventional moulds. A mould composition based on mono-aluminum phosphate (MAP) binders and MgO and molochite stuccos was developed which could be fired at temperatures as low as 650^{o}C (compared with 1000^{o}C for conventional moulds) while maintaining other essential mould properties. Such properties include green and fired strength, permeability and ease of removal after casting.

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Résumé

Ce projet a été commencé pour développer des moules céramique agglomeré à température basse pour les industries de moulage. Ces moules peuvent conserver de l'énergie durant le moulage parce que la température de coulée est plus bas qu'avec les moules conventionnel. Les moules nouveau sont composés de la matière d'agrégation phosphate mono-aluminium et le magnésie avec du stuc "molochite". En ajustant la composition, la température d'agglomération a pu etre réduit jusqu'à 650°C (comparer à 1000°C pour les moules conventionnel) sans perdre les propriétés requises comme la résistance à la rupture soit avant ou après l'agglomération, la perméabilité et la facilité d'enlever le moule après le moulage.

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1. INTRODUCTION

The development of ceramic moulds for investment casting has been ongoing at ORF for several years. The investment casting process is used to produce complex metal parts in a variety of alloys with close control of dimensions. Newer process developments have included the ability to directionally solidify parts or even cast single crystal components. The future of the investment casting industry is bright since increasingly complex castings are being used to reduce the number of parts in large assemblies and as advanced alloys are being developed and cast in high performance components. In order to meet the challenges posed by these changes, continuing development effort is required to keep Canadian industry at the forefront of this technology.

The refractory mould used in the casting process is an important area of study since it represents approximately 25% of the manufacturing cost, is usually fabricated from 100% imported materials and its quality is a key element in achieving a high level of productivity. Thus an improvement in mould quality and cost can make a significant contribution to the future development of the Canadian investment casting industry.

The initial ORF project was completed in September in 1982. This project was initiated to study the technology used in the fabrication of investment casting moulds, to improve the quality of the moulds and to reduce their cost. During the first project, background research into processes and binders was carried out, novel test equipment was constructed and experimental work was performed on the rheological and drying properties of slurries used in the process.

The second ORF project was initiated in April of 1983 to develop low temperature firing moulds to save energy during the firing process. Under Phase I of this program (from April to July 1983), significant progress was made with several laboratory-scale formulations being identified which were considered to have potential for further developments. Laboratory shell mould formulations prepared using novel

phosphate binders were developed which provided superior shell strength over moulds fabricated with conventional silica binders. The fired strengths of phosphate bonded test specimens fired at only 600°C were observed to be over 60% higher than specimens prepared using the standard DPC mould formulations and fired at 1000°C.

The experimental results achieved in Phase I indicated that high strength ceramic shell moulds could be achieved with low firing temperatures. However, further work to develop and understand the shell formulation was required before it could be used in the actual process. This work was performed in Phase II of the project, and was initiated in November of 1985. The work performed in Phase II, from November 1985 to March of 1987, is the subject of this report.

2. BACKGROUND INFORMATION

Investment casting, or lost wax casting as it is commonly known, uses a refractory mould that is produced by coating an expendable pattern with a refractory slurry which sets at room temperature. This expendable pattern is generally a wax or filled-wax blend. A brief description of the process begins with the preparation of an injection die allowing for the necessary contraction factor of the wax and the metal to be poured. Using this die, copies of the wax pattern may be injection moulded. Once the wax patterns have been produced and any flash removed, they are assembled onto a running and feeding system fabricated from the same wax. This is done by welding the wax parts together with a heated spatula.

After these wax assemblies, known as trees, have been cleaned, the first dip coat is applied. This is a slurry generally composed of an inorganic silicate binder and finely ground refractory flour. Together with a coating refractory grain (called stucco), this coating forms the inner surface of the shell and is thus responsible for the surface finish of the finished casting. Once the first slurry and stucco coat have thoroughly dried, further backup coats are applied, slurry and stucco alternately, until the required thickness of the shell mould is obtained.

Once this dipping process is complete, the next stage, as the common name implies, is to lose the wax. This is usually done by steam autoclave dewaxing.

Once the moulds have been dewaxed, they are fired and are then ready for metal pouring. Once the casting has solidified, the ceramic shell is broken away from the metal and discarded, leaving a casting which duplicates the wax part used as a pattern.

The key properties of moulds used in investment casting are the following.

(i) Green and Fired Strengths

Green and fired strengths are the most critical mould properties. High green and fired strengths are required for mould handling and to withstand the metal pouring process.

(ii) Permeability

The air permeability of the moulds is another critical property in that it determines how quickly and easily the molten metal can displace air in the mould. Without adequate permeability, defects such as pinholes occur on the cast surface.

(iii) Thermal Expansion Properties

The thermal expansion properties of the mould material determine the final dimensions of the cast piece. A mould which is dimensionally stable during the casting process will give better replication of the wax original. Thus a low thermal expansion coefficient at the relevant temperature is a required property.

These three properties were investigated in detail for the mould formulations developed throughout the course of the project.

3. EXPERIMENTAL PROGRAM AND RESULTS

3.1 Preliminary Work

Preliminary work in the project involved making up some test slurries using monomagnesium phosphate (MMP) and monoaluminum phosphate (MAP) binders. These initial experiments used a standard colloidal silica slurry with zircon sand stucco for the facecoat, followed by four backup coats using the phosphate binder slurries and molochite (calcined china clay) or MgO stuccos. The composition of the test strips is given in Table I. Details as to the slurry compositions are given in Appendix A. Ten strips were prepared for each composition.

None of the preliminary trials was successful. In the case of the MMP samples, the binder did not set, whereas in the case of the MAP samples, severe warpage in the direction of the facecoats was observed. This warpage was attributed to differing thermal expansion properties between the facecoat and the backup coats.

Other preliminary work investigated the compatibility of the phosphate binders with liquids other than water. This was performed to see if liquids more volatile than water (resulting in accelerated drying) could be substituted in the MAP/MMP systems. Liquids investigated were methanol, ethanol and isopropanol. In all cases, precipitation of phosphate salts occurred, indicating that these liquids were not compatible with the phosphate binders.

3.2 Shell Development - Strength Properties

In total, over 70 shell compositions were tested; for each composition 10 test strips were usually prepared, resulting in 20 samples (one from each side of the test strip). Half of the samples were fired, and the room temperature modulus of rupture (MOR) was measured for the green and fired samples. Complete details of all slurries prepared are given in Appendices B and C. Complete details of all compositions tested are given in Appendix D. The data presented in this section of the report have been extracted from these Appendices.

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TABLE I

TEST STRIP COMPOSITION

Facecoat			Backup Coats (X4)		
Slurry ID	Slurry Type	Stucco	Slurry ID	Slurry Type	Stucco
Standard	Colloidal Silica	Zircon Sand	BEM2	MMP	Molochite 30/80 X2 Molochite 16/30 X2
Standard	Colloidal Silica	Zircon Sand	BEM3	MMP	Molochite 30/80 X2 Molochite 16/30 X2
F608	Colloidal Silica	Zircon Sand	B603	MAP	Grefcan MgO 96% X4 *311 psi
F608	Colloidal Silica	Zircon Sand	B603	MAP	Kaiser MgO X4 *281 psi
F608	Colloidal Silica	Zircon Sand	B603	MAP	Molochite 30/80 X2 Molochite 16/30 X2 *1298 psi

* These three sets were fired at 1000°C for 1 hour. The average MOR of the samples is given beside the *.

3.2.1 MgO Stuccos

The slurries used in investment casting are acidic (pH ~2), and when the pH of the slurries is raised, the slurries are destabilized and gelling (setting) occurs. One method of raising the pH of the freshly dipped shell is by exposure to an alkaline atmosphere such as ammonia. This is the current practice at DPC. A possible alternative to this procedure is use of an alkaline refractory stucco. A candidate material for this is magnesium oxide.

Several different grades of magnesium oxide are available, and four were selected for these experiments. All the selected grades were non-reactive, i.e. upon exposure to water the hydration of the MgO to $Mg(OH)_2$ occurs minimally. The four types chosen were as follows.

(i) Grefcan 96% MgO deadburned
- General Refractories, Canada
- minus 18 mesh

(ii) Grefcan 98% MgO deadburned
- General Refractories, Canada
- minus 6, plus 20 mesh

(iii) Kaiser MgO deadburned
- Continental Refractories
- minus 6, plus 35 mesh

(iv) Teco 120S Electrofused MgO
- CE Refractories
- minus 60, sieved to plus 100 mesh at ORF

Experiments were performed using both colloidal silica and MAP binders. In addition, a standard colloidal silica/zircon sand/molochite shell was prepared for comparison purposes. The data are summarized in Figure 1.

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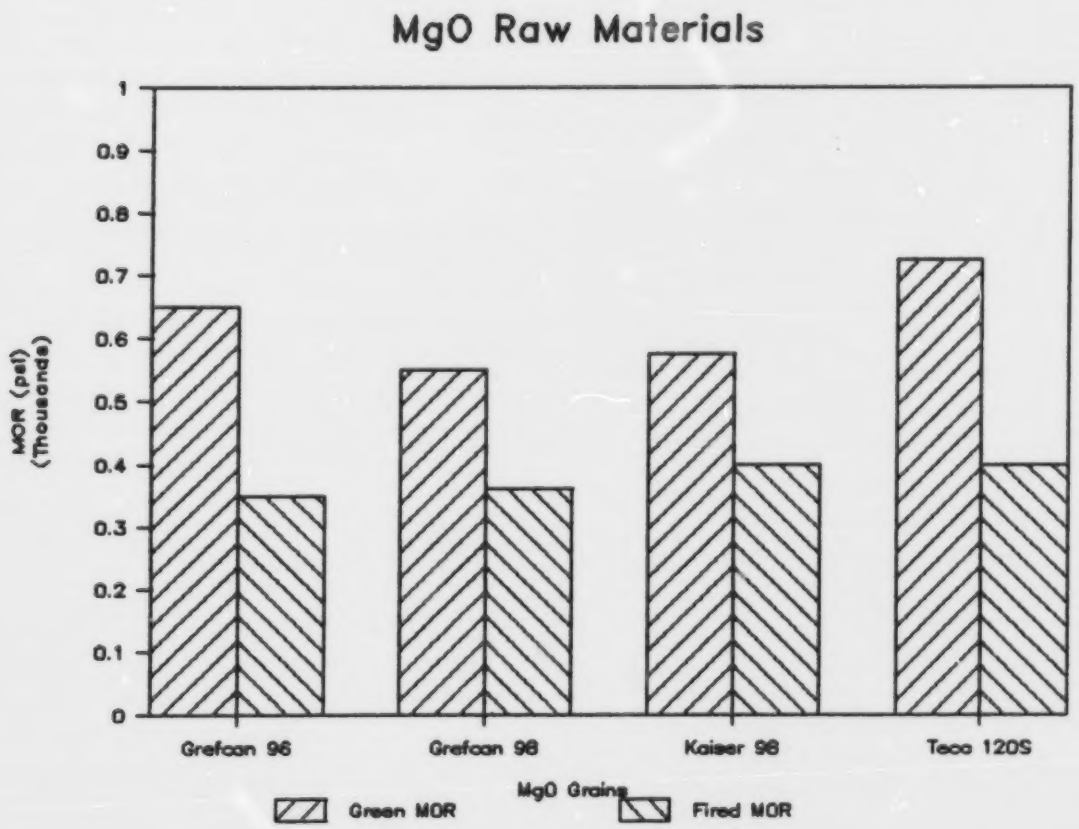
Figure 1



The data show that the MgO types are essentially similar; however, the Teco MgO, being the finest, is likely most suitable for facecoats. For subsequent experiments the Teco MgO was used for facecoats and the Kaiser MgO was used for backup coats.

3.2.2 MAP Concentration

To determine the effect of MAP concentration on the shell strengths, slurries with MAP levels ranging from 14 to 32 weight percent were prepared and used to make experimental shells. The data are summarized in Figure 2, and show that the MAP concentration has little effect on shell strengths; however, highest strengths were observed at an intermediate level of 23% MAP.

3.2.3 Zircon/Fused Silica Ratio

The MAP slurry contains zircon flour, fused silica and water. The zircon is used because it is not wetted by metals, and therefore contributes to easy demoulding of the paired metal. The fused silica is used because it is soluble in caustic (the medium used to remove the last traces of the mould material from the cast piece) and because it is low in thermal expansion, thereby contributing to dimensional stability. The zircon:fused silica ratio was adjusted from 2:1 to 0.67:1, data being summarized in Figure 3.

The data show that higher strengths are achieved at the highest zircon:fused silica ratio (i.e. 2:1). The effect of this higher ratio on mould solubility in caustic is not known, and in-plant trials would be necessary to test this.

3.2.4 Firing Temperature

The original objective of the project was to conserve energy by developing a shell which could be fired at temperatures lower than 1000^{o}C, yet retain sufficient strength for the casting of metal. Thus a series of experiments was initiated to determine the effect of firing temperature on the strength of both MAP/MgO and colloidal

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Figure 2

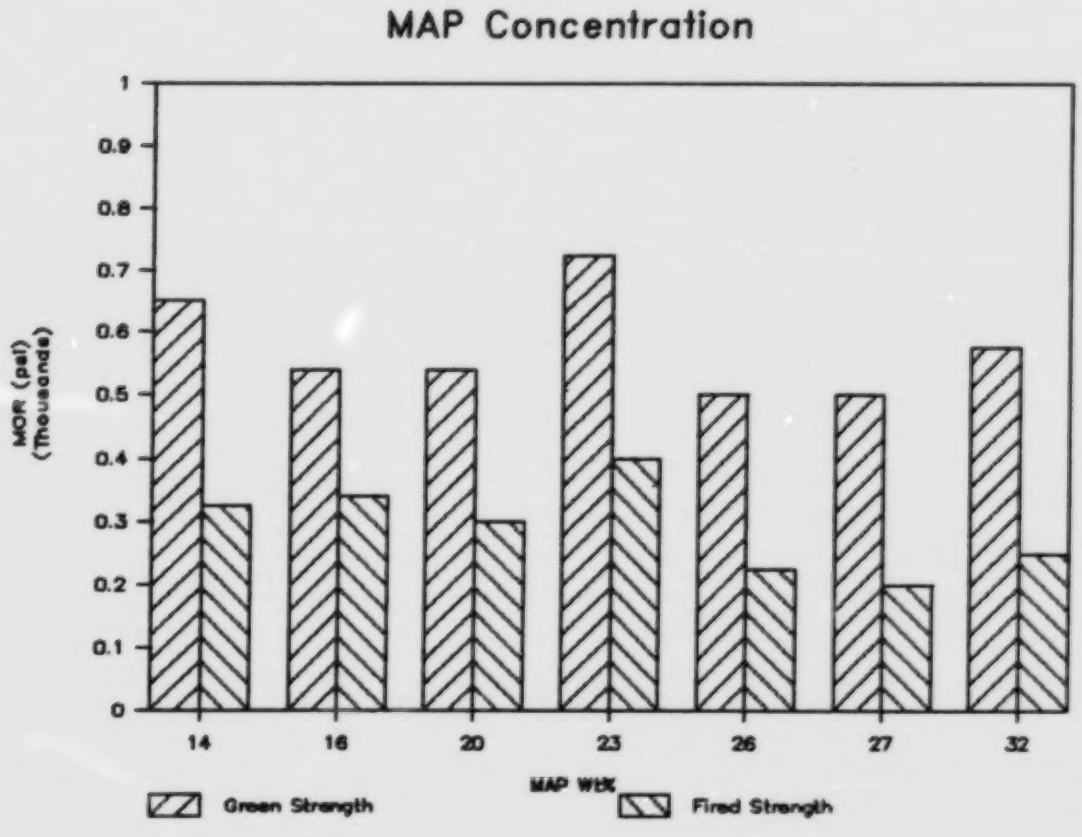

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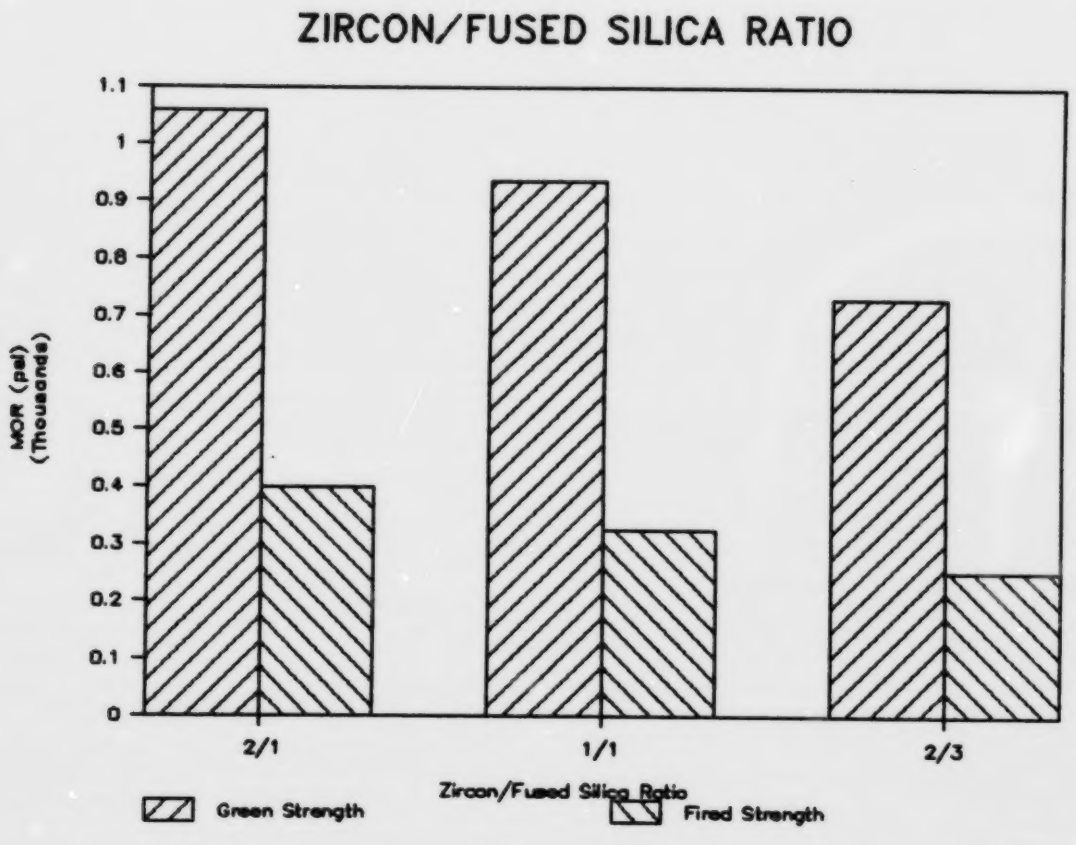
Figure 3



silica/molochite shells. Firing temperatures from 650°C to 1000°C were evaluated; the data are summarized in Figure 4.

The data show that the fired strength of the MAP/MgO shells is significantly below that of the colloidal silica/molochite shells at all temperatures; however, although the standard colloidal silica/molochite shells are strongest when fired at higher (1000°C) temperatures, firing them at lower temperatures may yield shells which are still sufficiently strong yet which are easier to remove. More about this will be discussed in the section on pouring trials.

A conclusion drawn from this series of experiments was that although the MAP/MgO system produced shells with good green strength, new stucco components were needed to improve the fired strength. This led to a series of experiments in which various molochite/MgO blends were used as the stucco material.

3.2.5 MgO/Molochite Blended Stucco

The MgO stucco is an excellent gelling agent for the MAP slurries, i.e. it gives good green strength to the shells; however, upon firing, strength development doesn't occur. In order to develop greater fired strength, molochite was introduced into the stucco blends. Blends with MgO contents ranging from 10 to 80 percent were prepared and used to stucco both MAP and colloidal silica based shells. The data for the MAP shells show that excellent green and fired strengths (fired at 650°C) were obtained with an MgO content of 20%; this is illustrated by Figure 5. The data from the 10% MgO samples are not included in this plot because of inconsistencies in the data. The standard molochite data refers to a colloidal silica/molochite shell fired at similar temperatures. When fired at 1000°C, the standard shell would have an MOR similar to the MAP/MgO:Molochite (20:80) shell fired at 650°C.

Although the MgO/Molochite blended stucco gave excellent green and fired strength, it was felt that some inconsistent results could be attributed to a separation of the MgO and molochite in the fluidized

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Figure 4

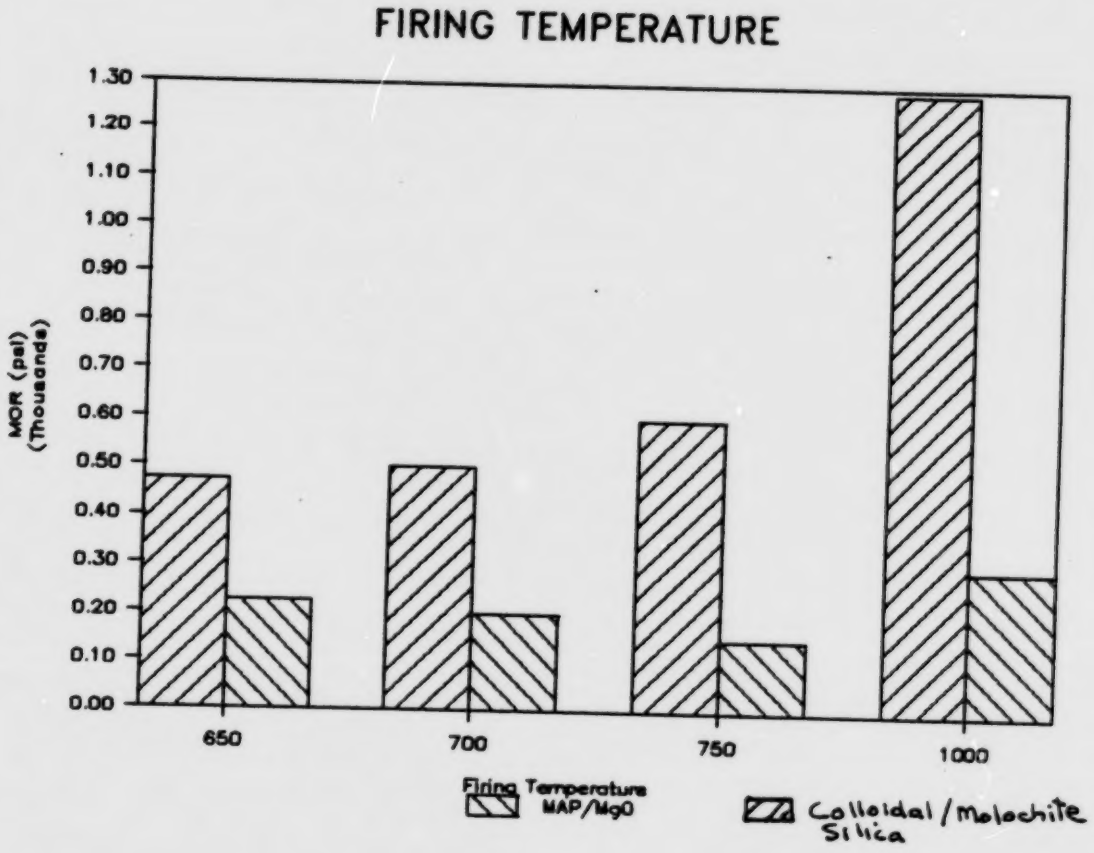

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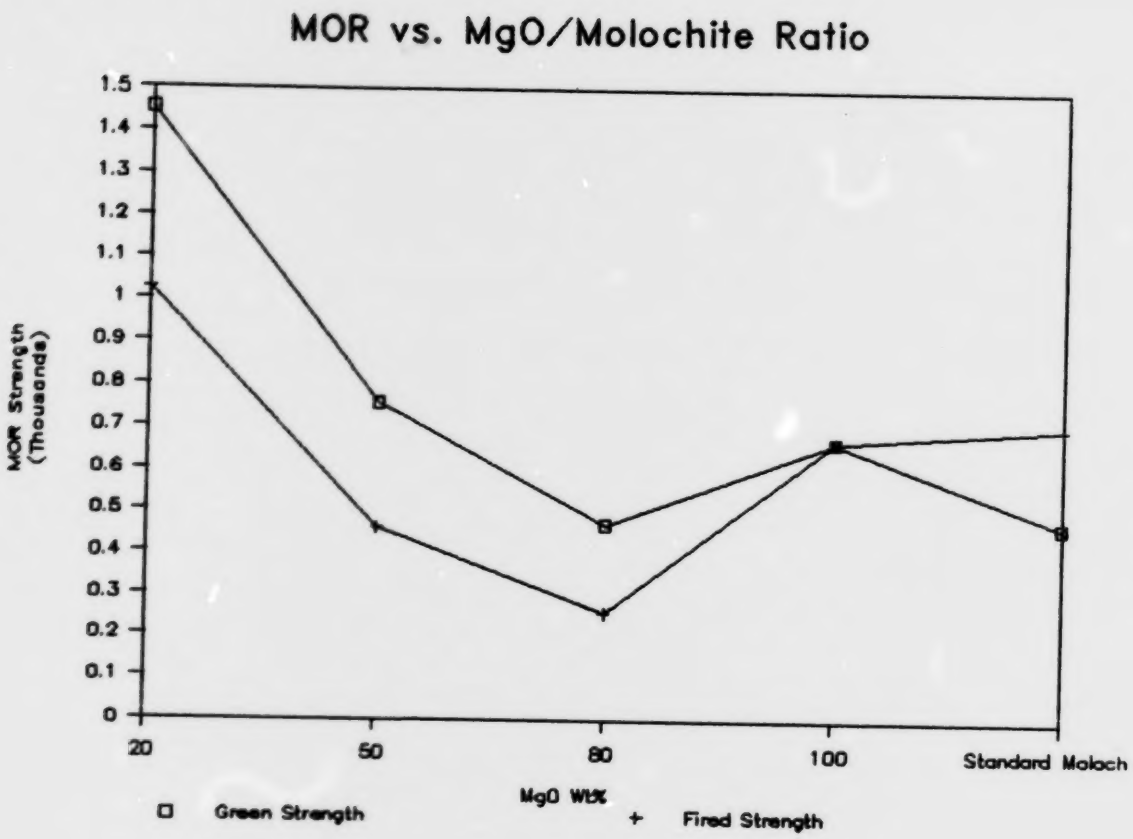
Figure 5



bed. The specific gravities of the two materials are very different (2.70 for molochite vs. 3.58 for MgO), resulting in the MgO staying ne the bottom section of the fluidized bed.

Although this can be partially overcome by having an MgO grind fine than the molochite, it will always be extremely difficult to ensure a homogeneous mix. To overcome this problem, MgO coated molochite was prepared by the following procedure.

The molochite was soaked in a 50% (w/w) Mg $(C_2H_3O_2)_2.4H_2O$ (hydrous magnesium acetate) solution for 1 hour, then passed through a 100 mesh sieve and dried and fired at 400°C for 2 hours. The firing was necessary to calcine the magnesium acetate to magnesium oxide. This procedure yielded MAP/MgO molochite shells with excellent green and fired strength. Details of this final shell composition and the strength data are given in Table II.

3.3 Shell Development - Thermal Expansion

An important property of investment casting moulds is thermal expansion. A low thermal expansion coefficient is necessary to maintain dimensional stability throughout the casting procedure. Throughout the experimental program, the coefficient of thermal expansion (CTE) of selected test shells was monitored.

The specimens were tested in a Harrop single push rod horizontal fused quartz dilatometer with an air atmosphere. A heating rate of 3°C per minute was used. Complete details of the thermal expansion tests are contained in Appendix E. A summary of the data is presented in Table III.

The data show that the goal of low CTE can be achieved only by including molochite as a stucco material. Molochite has a much lower CTE than MgO, and this is reflected in the expansion of the different shell compositions. The shells containing only MgO stucco have CTE

TABLE II

FINAL SHELL COMPOSITION AND STRENGTH DATA

TABLE II (a) Composition

Component	Description			
MAP Slurry	MAP 400 ml (0.645 kg)	Zircon Flour 1.107 kg	Fused Silica 0.721 kg	Water 216 g
Facecoat Stucco	MgO (Teco 70/170)			
Backup Stucco (1st two coats)	MgO coated molochite 30/80			
Backup Stucco (3rd and 4th coats)	MgO coated molochite 16/30			
Seal coat	MAP slurry as above			

TABLE II (b) Strength Data

Firing Temperature	Firing Time	MOR Green (psi)	MOR Fired (psi)
650°C	1 hour	1600 ± 352	1750 ± 77

TABLE III

SUMMARY OF THERMAL EXPANSION DATA

Shell ID	Shell Type	Average CTE (in./in./°C)
614W	Standard Coll. Silica/Zircon Molochite	2.61×10^{-6}
Standard DPC		3.22×10^{-6}
638	Ethyl Silicate/Colloidal Silica Hybrid Binder/Zircon/Molochite	2.97×10^{-6}
615W	MAP/MgO	8.05×10^{-6}
630TKM1	MAP/MgO/Molochite	4.57×10^{-6}
636TKM6	MAP/MgO/Molochite	3.53×10^{-6}
640MAC	MAP/MgO Coated Molochite	2.62×10^{-6}
641MAC	MAP/MgO Coated Molochite	3.91×10^{-6}

values over double those of the shells containing only zircon sand and molochite. However, in an MAP binder system, the MgO is necessary to obtain good green strength. A compromise is achieved with using MgO/molochite blends as the stucco material. This yields both adequate strength (as described earlier) and CTE values comparable to those of moulds currently prepared at DPC.

3.4 Permeability Measurements

An important property of the shell is its permeability, i.e. the ability of air to move through the shell during the casting of a piece. If the shell material is not sufficiently permeable, air will be retained in the mould, and the surface of the final piece will not be true with the wax original.

Initially the constant head water permeability of selected shells was measured until a facility for measuring gas permeability was set up at ORF. A summary of the water permeability data is given in Table IV. Complete details as to the composition of the shells are available in Appendix D. The data show that the MAP/MgO moulds have a higher water permeability than the colloidal silica molochite moulds.

TABLE IV

CONSTANT HEAD PERMEABILITY TEST RESULTS

Shell ID	Shell Type	Permeability Coefficient (cm/s)
610W	MAP/MgO	2.6×10^{-6}
613	MAP/MgO	3.19×10^{-6}
614W	Coll. Silica/Molochite	1.07×10^{-6}
615W	MAP/MgO	4.63×10^{-6}
616W	MAP/MgO	6.26×10^{-6}

A system was then set up to measure air permeability. Samples were prepared by the following procedure. A small hole was drilled in a table tennis ball, and a hollow glass tube was inserted into the hole and bonded with silicone sealer. After setting, the table tennis ball was dipped and stuccoed according to standard mould-making procedures. After setting, the mould was fired for one hour, during which the plastic table tennis ball was combusted from the sample. The glass tube was then connected to the permeability apparatus (a device to measure pressure differentials and gas flow), and the permeability was measured. Purified argon was the gas used. Because some samples were significantly more permeable than others, the pressure at which the gas flow was measured varies among the samples. For comparison purposes, the gas flow measurement for all samples was adjusted to an intermediate pressure value. A linear pressure/gas flow relationship was assumed, and although such an assumption is not strictly true, for the purposes of this study, and over the narrow pressure range that the assumption is made, it is considered adequate. A complete set of data is included in Appendix F. A summary of the air permeability data is given in Table V. Again, details as to shell composition are available in Appendix D.

The data show that in all cases the permeability of the shells is greater at higher firing temperatures. It is also difficult to ascertain from the data what minimum permeability would be required to ensure an adequate surface on the finished piece. However, a minimum gas flow of ~800 cm^3/min. at 0.5 psi would likely be more than sufficient. The data show that the MAP/MgO/Molochite system can easily produce shells which satisfy this criterion.

3.5 Chemical Composition

The chemical composition of selected fired shells was monitored by X-ray diffraction. The shells tested included a standard colloidal silica/molochite shell, MAP/MgO shells and various MAP/MgO/Molochite shells. The data are summarized in Table VI. The shells with molochite have mullite in the fired samples, whereas those with MgO have

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TABLE V

PERMEABILITY MEASUREMENTS

Shell ID	Shell Type	Firing Temperature (°C)	Adjusted Average Gas Flow (cm³/min.)
635TKM6	Coll. Silica/MgO/Molochite	1000	833
635TKM7	Coll. Silica/MgO/Molochite	1000	803
635TKM8	Coll. Silica/MgO/Molochite	650 1000	400 938
636TKM7	MAP/MgO/Molochite	650	413
637	Coll. Silica/Molochite	650 1000	133 310
638	Hybrid/Molochite	650 1000	390 530
640MAC	MAP/MgO Coated Molochite	650	1333
640TKM6	MAP/MgO/Molochite	650	1500
Standard DPC	Fired at ORF Fired at DPC	1000 1000	1105 920

TABLE VI

CHEMICAL COMPOSITION

Shell ID	Shell Type	Firing Temperature (°C)	Major Constituents
615W	MAP/MgO	650	Zircon, Periclase MgO
629	Coll. Silica/Molochite	1000	Zircon, Sillimanite, Mullite
630TKM0	MAP/MgO	650	Zircon, Periclase, MgO
630TKM1	MAP/MgO/Molochite	650	Zircon, Mullite, Trace of MgO (Periclase)
630TKM2	MAP/MgO/Molochite	650	Zircon, Mullite, Periclase MgO
630TKM3	MAP/MgO/Molochite	650	Zircon, Mullite, Periclase MgO

periclase MgO in the fired samples. The impact of the periclase on the shell performance will be discussed in the discussion section of this report.

3.6 Plant Trials

For the majority of the project, the work consisted of developing compositions and measuring properties on a laboratory scale. However, as very promising results were being obtained towards the end of the project, it was decided to make test shells to be used in actual pouring trials.

The first trial was performed on January 8, 1987. A MAP binder/MgO coated molochite stucco system was used. Towards the end of the trial (at the 3rd and 4th backup coats) the MgO coated molochite did not set adequately. This was attributed to high humidity and poor air circulation where they were being prepared. Of the sixteen samples prepared, all but five failed in the green state. The five remaining samples were dewaxed and fired at ORF.

The second trial was performed on January 13, 1987 using the same composition; shells were prepared both at ORF and DPC. The shells made at DPC dried slowly, and 6 out of 16 were damaged because they stuck together. The shells made at ORF maintained their integrity throughout the firing and dewaxing. However, the shells dewaxed at DPC disintegrated during the steam dewaxing. Complete details regarding the shell compositions are given in Appendix D. A summary is given in Table VII. The data show excellent green and fired strengths for all samples.

The dewaxed shells were used in pouring trials at DPC. No problems were encountered during the pouring procedure, and the cast pieces were equivalent to those obtained from the conventional DPC process.

TABLE VII

SHELL COMPOSITIONS

Shell ID	Shell Type	Average MOR Green (psi)	Fired (psi)
640MAC (dewaxed & fired at ORF)	MAP/MgO Coated Molochite	1724	1495
641MAC	MAP/MgO Coated	1320	1316
DPC	Molochite	1466	1557
641MAC	MAP/MgO Coated	1730	1663
ORF	Molochite		
Standard DPC made by DPC fired at ORF		1463	718

All samples fired at 650°C

4. DISCUSSION AND CONCLUSIONS

The overall objective of this project was to conserve energy in the investment casting process by developing ceramic mould compositions which could be fired at relatively low (~650^{o}C) temperatures. Other mould properties necessary for the precision casting of metal would be maintained in the developed formulations.

Overall, the objective of the project has been achieved, with mould compositions being developed which satisfy all criteria set, including a pilot scale pouring trial. This mould composition consists of an MAP/Zircon Flour/Fused Silica slurry and MgO/Molochite stucco. The MgO is included to give good green strength without exposure to ammonia, whereas the molochite is included to give good fired strength and a low thermal expansion coefficient. However, some problems still exist. The advantages and disadvantages of the developed process can be summarized as follows.

Advantages

(1) The mould firing temperature is lower than the conventional process (650^{o}C as opposed to 1000^{o}C).

(2) An ammonia atmosphere is not required to set the shell for adequate green strength.

(3) Preliminary work has shown that the developed composition withstands the pouring of molten metal and produces cast pieces comparable to those formed with conventional moulds.

Disadvantages

(1) The developed composition is soluble under autoclave conditions, and the mould is not suitable for autoclave dewaxing.

(2) The MgO/molochite stucco may be difficult to keep homogeneous in a fluidized bed. The alternative (coating the molochite with MgO) is time consuming and expensive.

Overall, the most practical solution would be to substitute an insoluble alkaline refractory material for the MgO. Materials worth investigating include rapid setting, high alumina cements.

In conclusion, the best shell developed at ORF is the following.

Slurry (all parts by weight)
~3 parts MAP
~5.5 parts Zircon Flour
~3.5 parts Fused Silica
~1 part water (adjusted to achieve viscosity)

Stucco
Facecoat: Electrofused MgO (70/170)
2 backup coats: Finer Molochite:MgO (80:20)
2 backup coats: Coarser Molochite:MgO (80:20)

The MgO coated molochite stucco has been eliminated because it is felt that is is impractical to synthesize it at the plant. This stucco, however, did give the best results.

5. RECOMMENDATIONS

There are two possible routes to pursue this project to its completion, i.e. the stage where DPC could be using the developed composition in the plant.

(i) Investigate the cost of converting the existing plant to the formulation as it exists, i.e. raw material cost, dry heat dewaxing cost, etc. Such an analysis would include the benefit of no longer using ammonia in the process.

(ii) Investigate replacements for MgO in the developed formulation which would be resistant to the autoclave dewaxing step, then perform the cost analysis above without the inconvenience of converting to dry heat dewaxing.

Final Report

It is felt that several promising alternatives for MgO replacement exist and that the second route would be the most logical at this stage. Such a program could be completed in a relatively short period of time, and would be expected to yield a commercially viable composition and process.

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APPENDIX A

Preliminary Work - Slurry Identification

Slurry ID	Final Composition		Viscosity Zahn #5 (sec.)
F601	Nalcoag 1050	1100 ml	
	Nalcast P2	1160 g	12
	Zircon Flour	1740 g	
F602	Nalcoag 1030	1010 ml	
	Nalcast P2	1363 g	12
	Zircon Flour	2044 g	
F603	Nalcoag 1030	1120 ml	
	Nalcast P2	1870 g	12
	Zircon Flour	1247 g	
F604	Nalcoag 1030	1055 ml	
	Nalcast P1W	1862 g	13
	Zircon Flour	1241 g	
F605	Nalcoag 1030	2400 ml	
	Celite 560	564	
	Celite 545	141	7
	Celite 512	440	
	Zircon Flour	2672 g	
F606	Nalcoag 1030	2000 ml	
	Nalcast P2	4000 g	10
	Zircon Flour	900 g	
F607	MMP	559 g	11
	H_2O	441 g	
	Nalcast P2	1644 g	
	Zircon Flour	2407 g	
F608	Nalcoag 1030	1720 ml	
	Nalcast P2	2 kg	10
	Zircon Flour	3 kg	
	Ultrawet	1 ml	
F609	Nalcoag 1030	1720 ml	
	Nalcast P2	3 kg	13
	Zircon Flour	2 kg	

Slurry ID	Final Composition		Viscosity Zahn #5 (sec.)
MMP Slurries			
BEM2	MMP	1020 g	
	H_2O	720 g	15
	Zircon Flour	2580 g	
	Fused SiO_2	1680 g	
BEM3	MMP	1410 g	
	H_2O	450 g	18
	Zircon Flour	2580 g	
	Fused SiO_2	1680 g	
Standard Colloidal Silica Slurry	Remasol SP30	1500 ml	
	Zircon Flour	3 kg	
	Nalcast P2 (Fused Silica)	2 kg	
B601	Nalcoag 6040	412 g	
	MAP	1186 g	
	Zircon Flour	2214 g	Thixotropic
	Nalcast P2 (Fused Silica)	1442 g	
	H_2O	250 ml	
B602	Nalcoag 1034A	412 g	
	MAP	1186 g	
	Zircon Flour	2214 g	11 (at 1 day)
	Nalcast P2	1442 g	
	H_2O	250 ml	
B603	MAP	1186 g	
	Zircon Flour	2214 g	
	Nalcast P2	1442 g	13 (at 2 days)
	H_2O	412 g	

APPENDIX B

MAP and MMP Slurry Compositions

MAP Slurry Compositions

Slurry ID	Final Composition: MAP (kg)	MAP (wt.%)	Zircon Flour (kg)	Fused Silica (kg)	Water (with ~0.2% ultra wet) (g)	Viscosity (Zahn #5) (when dipped): (sec.)	at (days)
B604	1.854	23	2.214	1.442	412	11	3
F610	1.308	24	2.057	1.543	469	23	7
F611	1.116	20	2.264	1.697	558	14	7
F612	1.00	17	2.468	1.853	668	16	7
F613	0.824	14	2.468	1.852	720	16	7
615	2.760	26	3.00	4.00	690	15	2
616	1.755	32	1.50	2.00	250	15	2
618	1.570	28	1.65	2.20	390	17	2
623	1.853	37	2.10	1.05	70	15	2
624	2.150	40	1.575	1.575	70	15	2
625	2.409	42	1.284	1.926	70	14	2
626	1.186	23	2.214	1.442	412	13	3
627	1.435	26	2.214	1.442	498	10	5
628	1.186	23	2.214	1.442	412	10	1
630	1.364	24	2.302	1.499	412	12	3
632	1.186	23	2.214	1.442	412	10.4	1
634	0.645	24	1.107	0.721	216	12	2
636	1.275	23	2.434	1.456	442	12	2
639	0.593	21	1.2179	0.7928	206	12	2
640*	2.372	22	4.650	2.994	324	12	1
641*	2.372	23	4.428	2.883	824	12	2

*Batches for Pilot Trials at DPC

MMP Slurry Compositions

Slurry ID	Final Composition: MAP (kg)	MAP (wt.%)	Zircon Flour (kg)	Fused Silica (kg)	Water (with ~0.2% ultra wet) (g)	Viscosity (Zahn #5) (when dipped) (sec.)	at (days)
617	1.26	25	1.50	2.0	315	13	2
619	1.56	28	1.65	2.2	240	13	1

Note: Fused Silica was Nalcast P2

APPENDIX C

Colloidal Silica and Ethyl Silicate Slurry Compositions

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Slurry ID	Colloidal Silica/ Ethyl Silicate Slurry Type	(kg)	(%)	Zircon Flour (kg)	Fused Silica (kg)	Viscosity (Zahn #5) (when dipped) (sec.)	at (days)
614	Nalcoag 1030	2.13	30	2.0	3.0	13	2
620	Nalcoag 1030	1.84	26	3.15 (+200 mesh)	2.1	13	1
621	Remasol SP30	1.82	26	3.15	2.1	12	1
622	Remet Silester A1	1.41	23	2.84 (+200 mesh)	1.89	12	1
629	Remasol SP30	1.85	26	3.21	2.14	15	3
631	Remasol SP30	1.82	26	3.15	2.10	12	2
633	Remasol SP30	1.89	27	3.0	2.0	12	2
635	Remasol SP30	2.26	27	3.6	2.4	12	2
637	Remasol SP30	1.83	27	3.0	2.0*	13	2
638	Silester A1	1.53	25	2.8	1.8*	13	2

*Fused Silica was Remet RP2, all others were Nalcast P2

ORF

APPENDIX D

Experimental Shells

ORE

Notes

(1) TEMO, KAMO and PEMO denote mixtures of MgO and Molochite. For specific details, refer to the end of this Appendix.

(2) MOR values are the average of a minimum of 6 samples. Usually, 10 samples were used in the calculation. If fewer samples than 6 were used, this is noted in the comments section.

(3) The hybrid binder is an ethyl silicate/colloidal silica hybrid binder.

(4) In all samples, a final seal coat of the backup slurry was applied after the last stucco coat.

MgO Molochite Blends

Finer Blends			Coarser Blends		
Stucco ID	Fused MgO TECO 120S +70 (%)	Molochite 30/80 (%)	Stucco ID	Fused MgO Kaiser (%)	Molochite 16/30 (%)
TEMO 1	20	80	KAMO 1	20	80
TEMO 2	50	50	KAMO 2	50	50
TEMO 3	80	20	KAMO 3	80	20
TEMO 4	80	20	KAMO 4	80	20
TEMO 5	70	30	KAMO 5	70	30
TEMO 5	10	90	KAMO 6	10	90
TEMO 7	20	80	KAMO 7	20	80
TEMO 8	30	70	KAMO 8	30	70

ORF

Shell ID	Face-coat Slurry ID	Face-coat Slurry Type	Face-coat Stucco	No. Face-coats	Backup Slurry ID	Backup Slurry Type	Backup Stucco	No. Backups	MOR Green Average Thickness (in.)	MOR Green Average Breaking Load (lb.)	MOR Green Average MOR (psi)	MOR Fired Average Thickness (in.)	MOR Fired Average Breaking Load (lb.)	MOR Fired Average MOR (psi)	Comments
609-96	F609	Coll. Silica	Zircon Sand	2	F609	Coll. Silica	Gref 96	4	0.226	14.5	649±109	0.225	7.7	351± 51	650, 1 hr.
609-98	F609	Coll. Silica	Zircon Sand	2	F609	Coll. Silica	Gref 98	4	0.267	19.0	553± 73	0.272	12.3	368± 40	650, 1 hr.
609-K	F609	Coll. Silica	Zircon Sand	2	F609	Coll. Silica	Kaiser MgO	4	0.247	16.1	585± 66	0.256	11.4	394± 46	650, 1 hr.
609-T	F609	Coll. Silica	Zircon Sand	2	F609	Coll. Silica	Teco MgO	4	0217	15.0	725± 57	0.218	8.5	402± 44	650,1 hr.
B604	B604	MAP	Teco MgO	2	B604	MAP	Gref 98	4	0.338	26.8	516± 62	0.368	13.2	193± 26	650, 1 hr.
F610	F610	MAP (23%)	Teco MgO	2	F610	MAP	Gref 96	4	0.273	23.9	722± 94	0.282	14.1	399± 59	650 (inm. of firing), 1 hr.
F611	F611	MAP (20%)	Teco MgO	2	F611	MAP	Kaiser MgO	4	0.301	20.8	536±130	0.302	12.4	307±111	650, 1 hr.
F612	F612	MAP (16%)	Teco MgO	2	F612	MAP	Kaiser MgO	4	0.289	19.0	540± 86	0.282	11.9	333± 64	650, 1 hr.
F613	F613	MAP (14%)	Teco MgO	2	F613	MAP	Kaiser MgO	4	0.280	22.9	662± 73	0.279	11.1	320± 33	650, 1 hr.
614M	614	Coll. Silica	Zircon Sand	1	614	Coll Silica	Molochite 30/80	2	0.276	13.1	386± 49	0.277	16.2	474± 32	650, 1 hr.
							Molochite 16/30	2				0.278	17.5	507± 54	700, 1 hr.
												0.283	21.3	602±145	750, 1 hr.
615M	615	MAP	Zircon Sand	1	615	MAP	Molochite 30/80	2	Disintegrated during dewatering			0.250	33.7	1247±324	650, 1 hr.
							Molochite 16/30	2	Saved 8 samples for fired MOR						

Shell ID	Face-coat Slurry ID	Face-coat Slurry Type	Face-coat Stucco	No. Face-coats	Backup Slurry ID	Backup Slurry Type	Backup Stucco	No. Backups	MOR						Comments
									Green			Fired			
									Average Thickness (in.)	Average Breaking Load (lb.)	Average MOR (psi)	Average Thickness (in.)	Average Breaking Load (lb.)	Average MOR (psi)	
615TK	615	MAP	Teco MgO	1	615	MAP	Kaiser MgO	4	0.248	13.5	490± 76	0.244	6.0	226± 40	650, 1 hr.
												0.249	5.2	204± 39	700, 1 hr.
												0.244	4.1	152± 27	750, 1 hr.
616TK	616	MAP	Teco MgO	1	616	MAP	Kaiser MgO	4	0.249	15.9	571± 81	0.253	8.0	274± 35	
617TK	617	MMP	Teco MgO	1	617	MMP	Kaiser MgO	4	Samples failed before dewaxing						1 hr. between coats
617TK2	617	MMP	Teco MgO	1	617	MMP	Kaiser MgO	4	0.266	17.4	571±151	Samples cracked after firing			2 hrs. between coats; avg. of 3
617TK4	617	MMP	Teco MgO	1	617	MMP	Kaiser MgO	4	0.274	16.0	477± 57	0.253	6.2	214± 46	4 hrs. between coats; avg. of 8, 650, 1 hr.
618TK1	618	MAP	Teco MgO	1	618	MAP	Kaiser MgO	4	0.255	14.0	494± 97	0.263	6.4	213± 42	1 hr. between coats; 650, 1 hr.
618TK2	618	MAP	Teco MgO	1	618	MAP	Kaiser MgO	4	0.239	19.0	749± 59	0.250	6.7	241± 39	2 hrs. between coats; 650, 1 hr.
618TK4	618	MAP	Teco MgO	1	618	MAP	Kaiser MgO	4	0.258	15.4	509± 80	0.255	6.3	217± 35	4 hrs. between coats; 650, 1 hr.
618M4	618	MAP	Zircon Sand	1	618	MAP	Molochite 30/80	2	--Remained soft, discarded--						4 hrs. between coats
							Molochite 16/30	2							
619TK	619	MMP	Teco MgO	1	619	MMP	Kaiser MgO	4	--Separated from wax strips; cracked; discarded						1 hr. between coats

Shell ID	Face-coat Slurry ID	Face-coat Slurry Type	Face-coat Stucco	No. Face-coats	Backup Slurry ID	Backup Slurry Type	Backup Stucco	No. Backups	MOR Green Average Thickness (in.)	MOR Green Average Breaking Load (lb.)	MOR Green Average MOR (psi)	MOR Fired Average Thickness (in.)	MOR Fired Average Breaking Load (lb.)	MOR Fired Average MOR (psi)	Comments
620	F608	Coll. Silica	Zircon Sand	1	620	Coll. Silica	Molochite 30/80	2	0.319	20.4	454± 39	0.320	26.8	575± 42	750°C, 1 hr.
							Molochite 16/30	2				0.317	29.7	659± 75	1000°C, 1 hr.
621	F608	Coll. Silica	Zircon Sand	1	621	Coll. Silica	Molochite 30/80	2	0.305	20.3	489± 50	0.312	28.0	639± 50	750°C, 1 hr.
							Molochite 16/30	2				0.321	29.1	625± 62	1000°C, 1 hr.
622	F608	Hybrid	Zircon Sand	1	622	Coll. Silica	Molochite 30/80	3	0.234	26.8	1115± 81	0.234	31.0	1284± 78	750°C, 1 hr.
							Molochite 16/30	2				0.243	26.9	1032± 63	1000°C, 1 hr.
623A	621	Coll. Silica	Zircon Sand	1	623	MAP	Teco MgO	1	0.256	31.6	1062± 69	0.249	10.8	390± 20	650°C, 1 hr.
							Kaiser MgO	4							
623B	626	MAP	Teco MgO	1	623	MAP	Teco MgO	1	0.245	20.9	787± 93	0.240	9.2	359± 47	600°C, 1 hr.
							Kaiser MgO	4				0.241	8.9	341± 41	650°C, 1 hr.
												0.249	8.8	316± 38	550°C, 1 hr.
624A	621	Coll. Silica	Zircon Sand	1	624	MAP	Teco MgO	1	0.262	29.1	957±123	0.253	8.9	312± 52	650°C, 1 hr.
							Kaiser MgO	4							
624B	626	MAP	Teco MgO	1	624	MAP	Kaiser MgO	4	0.242	17.4	658± 72	0.232	6.4	265± 31	650°C, 1 hr.
625A	621	Coll. Silica	Zircon Sand	1	625	MAP	Teco MgO	1							
							Kaiser MgO	4	0.259	22.1	734±124	0.267	8.3	261± 35	650°C, 1 hr.
625B	626	MAP	Teco MgO	1	625	MAP	Kaiser MgO	4	0.254	18.6	650±101	0.249	6.9	249± 39	650°C, 1 hr.

Shell ID	Face-coat Slurry ID	Face-coat Slurry Type	Face-coat Stucco	No. Face-coats	Backup Slurry ID	Backup Slurry Type	Backup Stucco	No. Backups	MOR Green Average Thickness (in.)	MOR Green Average Breaking Load (lb.)	MOR Green Average MOR (psi)	MOR Fired Average Thickness (in.)	MOR Fired Average Breaking Load (lb.)	MOR Fired Average MOR (psi)	Comments
626M	626	MAP	Molochite 30/80	2	626	MAP	Molochite 16/30	3	-Some fell off wax surface-						
626ZM	626	MAP	Zircon Sand	1	626	MAP	Molochite 30/80 Molochite 16/30	2 2	0.222	7.8	353± 44	0.231	15.0	642±206	Cured in ammonia; 650°C, 1 hr., Avg. of 3
626TM	626	MAP	Teco MgO	1	626	MAP	Molochite 30/80 Molochite 16/30	2 2	0.225	8.6	381± 49	0.220	11.1	508± 65	Cured in ammonia; 650°C, 1 hr., Avg. of 6
628TMC	628	MAP	Teco MgO	1	628	MAP	Mag. Chem 30 Mag. Chem 12 x 40	2 2	0.197	7.08	418± 65	0.200	5.1	297± 72	650°C, 1 hr.
628TK	628	MAP	Teco MgO 70/170	1	628	MAP	Teco MgO +70 Kaiser MgO	2 2	0.207	12.4	655±108	0.210	4.4	226± 55	650°C, 1 hr.
628TF	628	MAP	Teco MgO 70/170	1	628	MAP	Forsterite 30/70 Forsterite 20/201	2 2	0.244	34.7	1334±223	0.237	11.9	483± 75	650°C, 1 hr.
629	629	Coll. Silica	Zircon Sand	1	629	MAP	Molochite 30/80 Molochite 16/30	2 2	0.253	13.2	467± 43	0.246	18.7	701± 83	1000°C, 1 hr.
630TKM1	630	MAP	Teco MgO 70/170	1	630	MAP	TEMO 1 KAMO	2 2	0.216	29.8	1454	0.211	19.6	1028±185	650°C, 1 hr.

Shell ID	Face-coat Slurry ID	Face-coat Slurry Type	Face-coat Stucco	No. Face-coats	Backup Slurry ID	Backup Slurry Type	Backup Stucco	No. Backups	MOR Green Average Thickness (in.)	MOR Green Average Breaking Load (lb.)	MOR Green Average MOR (psi)	MOR Fired Average Thickness (in.)	MOR Fired Average Breaking Load (lb.)	MOR Fired Average MOR (psi)	Comments
630TKM2	630	MAP	Teco MgO 70/170	1	630	MAP	TEMO 2 KAMO 2	2 2	0.223	16.5	756±198	0.228	10.7	461± 95	650°C, 1 hr.
630TKM3	630	MAP	Teco MgO 70/170	1	630	MAP	TEMO 3 KAMO 3	2 2	0.218	9.7	468±125	0.220	5.4	255± 51	650°C, 1 hr.
630TKMO	630	MAP	Teco MgO 70/170	1	630	MAP	Teco MgO +70 Kaiser MgO	2 2	0.212	13.1	665± 59	0.212	6.4	325± 55	650°C, 1 hr.
631	631	Coll. Silica	Zircon Sand	1	631	Coll. Silica	Molochite 30/80 Molochite 16/30	2 2	0.257	13.2	453± 37	0.238	12.7	542± 58	1000°C, 1 hr.
631TKM4	631	Coll. Silica	Teco MgO 70/170	1	631	Coll. Silica	TEMO 4 KAMO 4	2 2	0.224	7.1	321± 39	0.232	3.5	173± 17	1000°C, 1 hr.
631TKM5	631	Coll. Silica	Teco MgO 70/170	1	631	Coll. Silica	TEMO 5 KAMO 5	2 2	0.232	7.6	321± 59	0.233	4.7	197± 38	1000°C, 1 hr.
631TKM6	631	Coll. Silica	Teco MgO 70/170	1	631	Coll. Silica	TEMO 6 KAMO 6	2 2	0.235	6.2	255± 34	0.237	5.4	217± 38	1000°C, 1 hr.
632TKM6	632	MAP	Teco MgO 70/170	1	632	MAP	TEMO 6 KAMO 6	2 2	0.201	5.6	333±131	0.212	3.2	169± 42	650°C, 1 hr.
633	633	Coll. Silica	Zircon Sand	1	633	Coll. Silica	Molochite 30/80 Molochite 16/30	2 2	0.263	13.0	441±105	0.251	15.2	547± 79	1000°C, 1 hr.

Shell ID	Face-coat Slurry ID	Face-coat Slurry Type	Face-coat Stucco	No. Face-coats	Backup Slurry ID	Backup Slurry Type	Backup Stucco	No. Backups	MOR Green Average Thickness (in.)	MOR Green Average Breaking Load (lb.)	MOR Green Average MOR (psi)	MOR Fired Average Thickness (in.)	MOR Fired Average Breaking Load (lb.)	MOR Fired Average MOR (psi)	Comments
633TKM4	633	Coll. Silica	Teco MgO 70/170	1	633	Coll. Silica	TEMO 4 KAMO 4	2 2	0.225	6.6	303± 62	0.226 0.225	5.8 4.1	261± 50 190± 34	650°C, 1 hr. 1000°C, 1 hr.
633TKM5	633	Coll. Silica	Teco MgO 70/170	1	633	Coll. Silica	TEMO 5 KAMO 5	2 2	0.225	7.2	325± 54	0.211 0.218	5.6 5.4	288± 52 260± 46	650°C, 1 hr. 1000°C, 1 hr.
633TKM6	633	Coll. Silica	Teco MgO 70/170	1	633	Coll. Silica	TEMO 6 KAMO 6	2 2	0.219	8.8	416± 49	0.218 0.216	9.6 9.2	463± 37 450± 65	650°C, 1 hr. 1000°C, 1 hr.
634TKM6	634	MAP	Teco MgO 70/170	1	634	MAP	TEMO 6 KAMO 6	2 2	0.230	25.0	1104±130	0.239	26.8	1071±186	650°C, 1 hr.
635	635	Coll. Silica	Zircon Sand	1	635	Coll. Silica	Molochite 30/80 Molochite 16/30	2 2	0.225	8.0	378± 74	0.214	9.9	481± 51	1000°C, 1 hr.
635TKM6	635	Coll. Silica	Zircon Sand	1	635	Coll. Silica	TEMO 6 KAMO 6	2 2	0.211	6.4	327± 32	0.212 0.213	6.8 7.3	340± 24 366± 45	650°C, 1 hr. 1000°C, 1 hr.
635TKM6/ MAP	635	Coll. Silica	Zircon Sand	1	635	Coll. Silica	TEMO 6 KAMO 6	2 2	0.218	5.0	244±112	0.210	4.7	242± 43	Each backup coat sprayed with MAP, 650°C, 1 hr.
635TKM7	635	Coll. Silica	Zircon Sand	1	635	Coll. Silica	TEMO 7 KAMO 7	2 2	0.221	6.0	282± 31	0.229 0.212	7.5 8.2	326± 35 376± 30	650°C, 1 hr. 1000°C, 1 hr.
635TKM7/ MAP	635	Coll. Silica	Zircon Sand	1	635	Coll. Silica	TEMO 7 KAMO 7	2 2	0.220	3.7	174± 38	0.225	4.6	207± 14	Each backup coat sprayed with MAP, 650°C, 1 hr.

Shell ID	Face-coat Slurry ID	Face-coat Slurry Type	Face-coat Stucco	No. Face-coats	Backup Slurry ID	Backup Slurry Type	Backup Stucco	No. Backups	MOR Green Average Thickness (in.)	MOR Green Average Breaking Load (lb.)	MOR Green Average MOR (psi)	MOR Fired Average Thickness (in.)	MOR Fired Average Breaking Load (lb.)	MOR Fired Average MOR (psi)	Comments
635TKM8	635	Coll. Silica	Zircon Sand	1	635	Coll. Silica	TEMO 8	2	0.242	6.8	262± 37	0.231	7.9	330± 23	650°C, 1 hr.
							KAMO 8	2				0.232	8.5	343± 32	1000°C, 1 hr.
635TKM8/ MAP	635	Coll. Silica	Zircon Sand	1	635	Coll. Silica	TEMO 8	2	0.223	3.4	156± 23	0.216	4.5	217± 30	Each backup coat sprayed with MAP, 650°C, 1 hr.
							KAMO 8	2							
636TKM6	636	MAP	Teco MgO 70/170	1	636	MAP	TEMO 6	2	0.213	16.8	855±131	0.208	11.8	761± 86	650°C, 1 hr.
							KAMO 6	2							
636TKM7	636	MAP	Teco MgO 70/170	1	636	MAP	TEMO 7	2	0.202	21.2	1184±161	0.209	22.8	1192±126	650°C, 1 hr.
							KAMO 7	2							
636TKM8	636	MAP	Teco MgO 70/170	1	636	MAP	TEMO 8	2	0.211	18.2	931± 89	0.214	17.9	965±142	650°C, 1 hr.
							KAMO 8	2							
637	637	Coll. Silica	Zircon Sand	1	637	Coll. Silica	Molochite 30/80	2	0.237	13.2	514± 43	0.227	16.7	728±116	650°C, 1 hr.
								2							
							Molochite 16/30	2				0.228	20.6	887±109	1000°C, 1 hr.
												0.227	17.3	742±139	1000°C, 1 hr.
638	638	Hybrid	Zircon Sand	1	638	Hybrid	Molochite 30/80	2	0.197	17.2	1005±132	0.183	19.2	1267±195	650°C, 1 hr.
							Molochite 16/30	2				0.191	17.5	1088± 85	1000°C, 1 hr.
												0.194	16.1	974±175	1000°C, 14 hr.
639	639	MAP	Teco MgO 70/170	1	639	MAP	TEMO 6	2	0.230	48.2	2068±140	0.224	48.2	2164±120	650°C, 1 hr.
							KAMO 6	6	0.246	28.9	1089± 38	0.275	15.3	459± 4	650°C, 1 hr., each B.U. coat dusted with MgO, 2 samples

Shell ID	Face-coat Slurry ID	Face-coat Slurry Type	Face-coat Stucco	No. Face-coats	Backup Slurry ID	Backup Slurry Type	Backup Stucco	No. Backups	MOR Green Average Thickness (in.)	MOR Green Average Breaking Load (lb.)	MOR Green Average MOR (psi)	MOR Fired Average Thickness (in.)	MOR Fired Average Breaking Load (lb.)	MOR Fired Average MOR (psi)	Comments
639M	639	MAP	Teco MgO 70/170	1	639	MAP	Molochite 30/80	2	0.294	23.4	628±158	0.289	28.0	754±102	Molochite stucco, with MgO after to aid gelling, 650°C, 1 hr.
							Teco MgO-170								
							Molochite 16/30	2							
							Teco MgO-170								
639MAC	639	MAP	Teco MgO 70/170	1	639	MAP	Molochite 30/80	2	0.220	34.7	1602±352	0.230	41.7	1750± 77	Molochite treated with magnesium acetate and heat prior to use, 650°C, 1 hr, each B.U. coat dusted with MgO, 2 samples
							Molochite 16/30	2	0.238*	40.1	1604±110	0.229	28.8	1233± 11	
639DPC	639	MAP	Teco MgO 70/170	1	639	MAP	TEMO 6	2							Shells from DPC
							KAMO 6	2							
640MAC	640	MAP	Teco MgO 70/170	1	640	MAP	Molochite 30/80	2	0.201	31.1	1724± 37	0.205	27.7	1495±131	Molochite treated with magnesium acetate and heat treated prior to use; 650°C, 1 hr.
							Treated	2		Made at DPC (avg. of 5)					
							Molochite 16/30 Treated			Made at ORF					
640TKM6	640	MAP	Teco MgO 70/170	1	640	MAP	TEMO 6	2	0.213	32.5	1636±448	0.212	34.5	1721±372	650°C, 1 hr.
							KAMO 6	2							
640TPM6	640	MAP	Teco MgO 70/170	1	640	MAP	TEMO 6	2	0.205	43.3	2350±178	0.188	31.0	2019±281	650°C, 1 hr., (avg. of 5)
							PEMO 6	2							

Shell ID	Face-coat Slurry ID	Face-coat Slurry Type	Face-coat Stucco	No. Face-coats	Backup Slurry ID	Backup Slurry Type	Backup Stucco	No. Backups	MOR Green Average Thickness (in.)	MOR Green Average Breaking Load (lb.)	MOR Green Average MOR (psi)	MOR Fired Average Thickness (in.)	MOR Fired Average Breaking Load (lb.)	MOR Fired Average MOR (psi)	Comments
641MAC/ DPC	641	MAP	Teco MgO 70/170	1	640	MAP	Molochite 30/80 Treated	2	0.236	32.2	1320±287	0.233	30.8	1316±161	650°C, 1 hr., (avg. of 4)
							Molochite 16/30 Treated	2	0.336	73.0	1466± 18	0.347	83.0	1557± 69	6 backup coats, avg. of 2
641MAC/ ORF	641	MAP	Teco MgO 70/170	1	641	MAP	Molochite 30/80 Treated	2	0.203	31.1	1730+236	0.212	31.9	1663±164	650°C, 1 hr.
							Molochite 16/30 Treated	2							
DPC	----Prepared at DPC with standard procedure----								0.269	44.9	1463±175	0.284	24.9	718± 49	

APPENDIX E

Thermal Expansion Data

ORF

Shell ID	Face-coat Slurry ID	Face-coat Slurry Type	Face-coat Stucco	No. Face-coats	Backup Slurry ID	Backup Slurry Type	Backup Stucco	No. Backups	Temp. Range of Avg. CTE (°C)	Average CTE (in./in./°C)
614W	614	Coll. Silica	Zircon Sand	1	614	Coll. Silica	Molochite 30/80 Molochite 16/30	2 9	200 - 750	2.6×10^{-6}
615W	615	MAP	Teco MgO	1	615	MAP	Kaiser MgO	11	200 - 750	8.05×10^{-6}
616W	616	MAP	Teco MgO	1	616	MAP	Kaiser MgO	11	200 - 750	8.01×10^{-6}
628TMC	628	MAP	Teco MgO	1	628	MAP	Mag. Chem 30 Mag. Chem 12 x 40	2 2	200 - 750	4.52×10^{-6}
628TF	628	MAP	Teco MgO 70/170	1	628	MAP	Forsterite 30/70 Forsterite 10/20	2 2	200 - 750	6.91×10^{-6}
629	629	Coll. Silica	Zircon Sand	1	629	MAP	Molochite 30/80 Molochite 16/30	2 2	200 - 750	2.86×10^{-6}
630TKM1	630	MAP	Teco MgO 70/170	1	630	MAP	TEMO 1 KAMO 1	5 5	200 - 750	4.57×10^{-6}
630TKM2	630	MAP	Teco MgO 70/170	1	630	MAP	TEMO 2 KAMO 2	5 5	200 - 750	4.68×10^{-6}
630TKM3	630	MAP	Teco MgO 70/170	1	630	MAP	TEMO 3 KAMO 3	2 2	200 - 750	6.6×10^{-6}
630TKMO	630	MAP	Teco MgO 70/170	1	630	MAP	Teco MgO +70	2	200 - 750	7.56×10^{-6}
636TKM6	636	MAP	Teco MgO 70/170	1	636	MAP	TEMO 6 KAMO 6	2 2	200 - 750	3.53×10^{-6}
638	638	Hybrid	Zircon Sand	1	638	Hybrid	Molochite 30/80 Molochite 16/30	2	200 - 750	2.97×10^{-6}

Shell ID	Face-coat Slurry ID	Face-coat Slurry Type	Face-coat Stucco	No. Face-coats	Backup Slurry ID	Backup Slurry Type	Backup Stucco	No. Backups	Temp. Range of Avg. CTE (^{o}C)	Average CTE (in./in./^{o}C)
640TKM6	640	MAP	Teco MgO 70/170	1	640	MAP	TEMO 6	2	200 - 640	3.71×10^{-6}
							KAMO 6	2		
640MAC	640	MAP	Teco MgO 70/170	1	640	MAP	Molochite 30/80 Treated	2	200 - 750	2.62×10^{-6}
							Molochite 16/30 Treated	2		
641MAC	641	MAP	Teco MgO 70/170	1	640	MAP	Molochite 30/80 Treated	2	200 - 640	3.91×10^{-6}
							Molochite 16/30 Treated	2		
Standard DPC									200 - 750	3.22×10^{-6}

ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM 'CTE' VERSION 83/9/19 Glass & Ceramics Centre

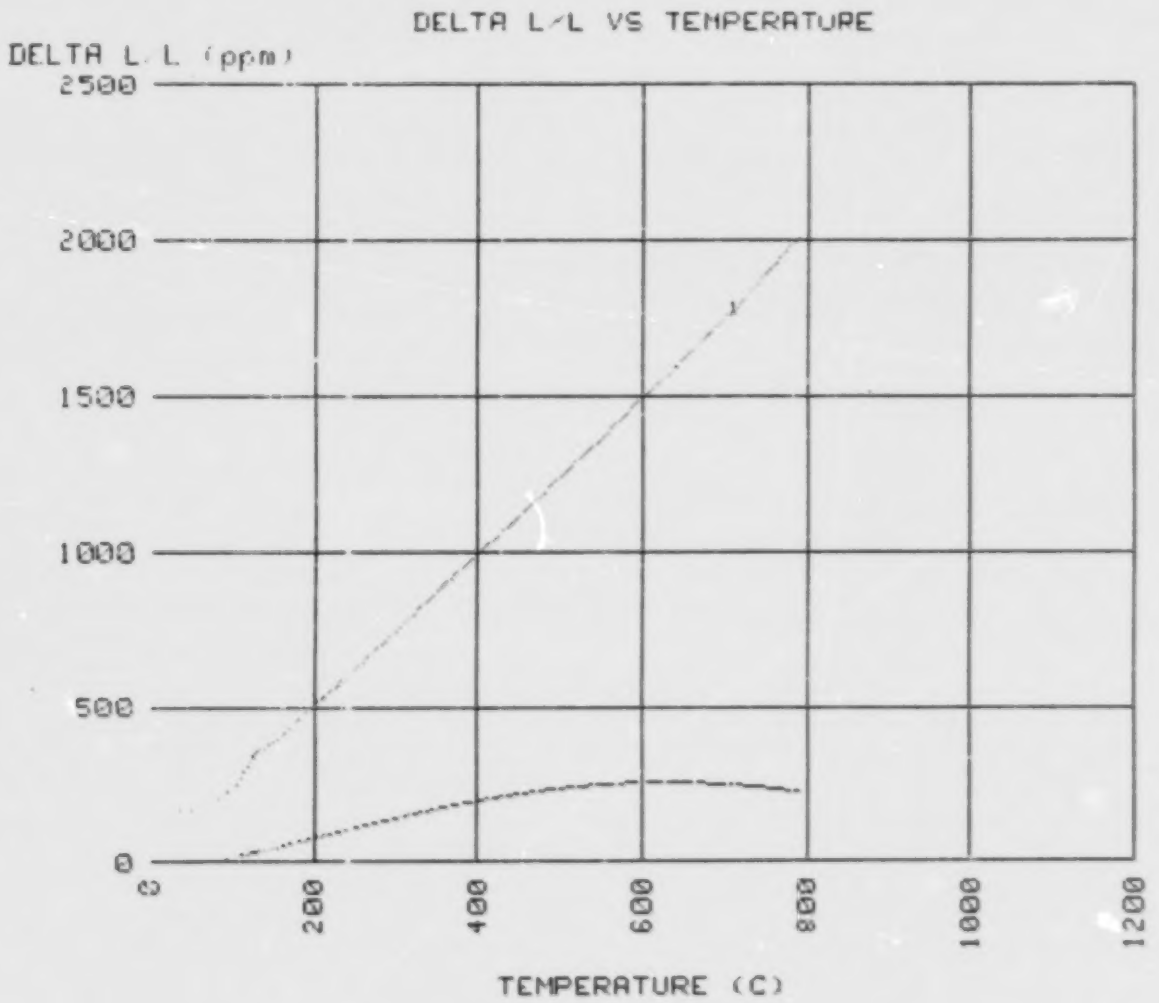
DATE AND TIME OF REPORT 04:04:17:08:01

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	614W/650 DEG C/1H
DATE OF RUN	04:04
RUN NUMBER	1
HP85 DATA FILE	614W
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.0085
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	3.94 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	614W
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	DELTA L / L MEAS. ppm	DELTA L / L CORRECTED ppm	%NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29163	29127	146	0.00
6	0	0	0	0	0.00
11	0	0	0	0	0.00
16	0	0	0	0	0.00
21	68	29171	29167	191	2.83
26	116	29250	29274	290	2.06
31	129	29300	29332	350	4.59
36	150	29322	29367	387	1.78
41	174	29365	29426	443	2.27
46	-193	29396	29469	488	2.45
51	213	29430	29516	535	2.30
56	232	29464	29563	582	2.42
61	251	29497	29608	627	2.41
66	270	29531	29654	673	2.49
71	288	29565	29700	718	2.50
76	305	29596	29743	761	2.43
81	323	29631	29787	805	2.47
86	340	29661	29827	847	2.43
91	357	29696	29871	889	2.49
96	374	29727	29911	930	2.44
101	392	29761	29954	972	2.39
106	408	29792	29993	1012	2.47
111	424	29824	30033	1052	2.47
116	441	29859	30074	1094	2.47
121	457	29893	30115	1134	2.45
126	473	29927	30155	1174	2.52
131	489	29962	30195	1214	2.52
136	504	29996	30234	1252	2.49
141	521	30032	30274	1293	2.51
146	536	30066	30314	1332	2.47
151	552	30104	30353	1371	2.47

156	568	30140	30392	1411	2.60
161	583	30178	30431	1451	2.52
166	599	30217	30472	1491	2.62
171	614	30253	30539	1528	2.39
176	630	30294	30550	1569	2.64
181	645	30338	30586	1605	2.44
186	660	30370	30628	1646	2.73
191	675	30414	30668	1687	2.68
196	690	30454	30705	1724	2.53
201	705	30500	30749	1765	2.71
206	719	30539	30786	1804	2.73
211	734	30586	30828	1848	2.99
216	749	30635	30874	1893	3.04
221	763	30676	30911	1932	2.73
226	777	30728	30958	1976	3.06
231	792	30778	31002	1207	-53.13

Date:04:04:17:08:01 Sample:614W/650 DEG C/1H Data File:614W



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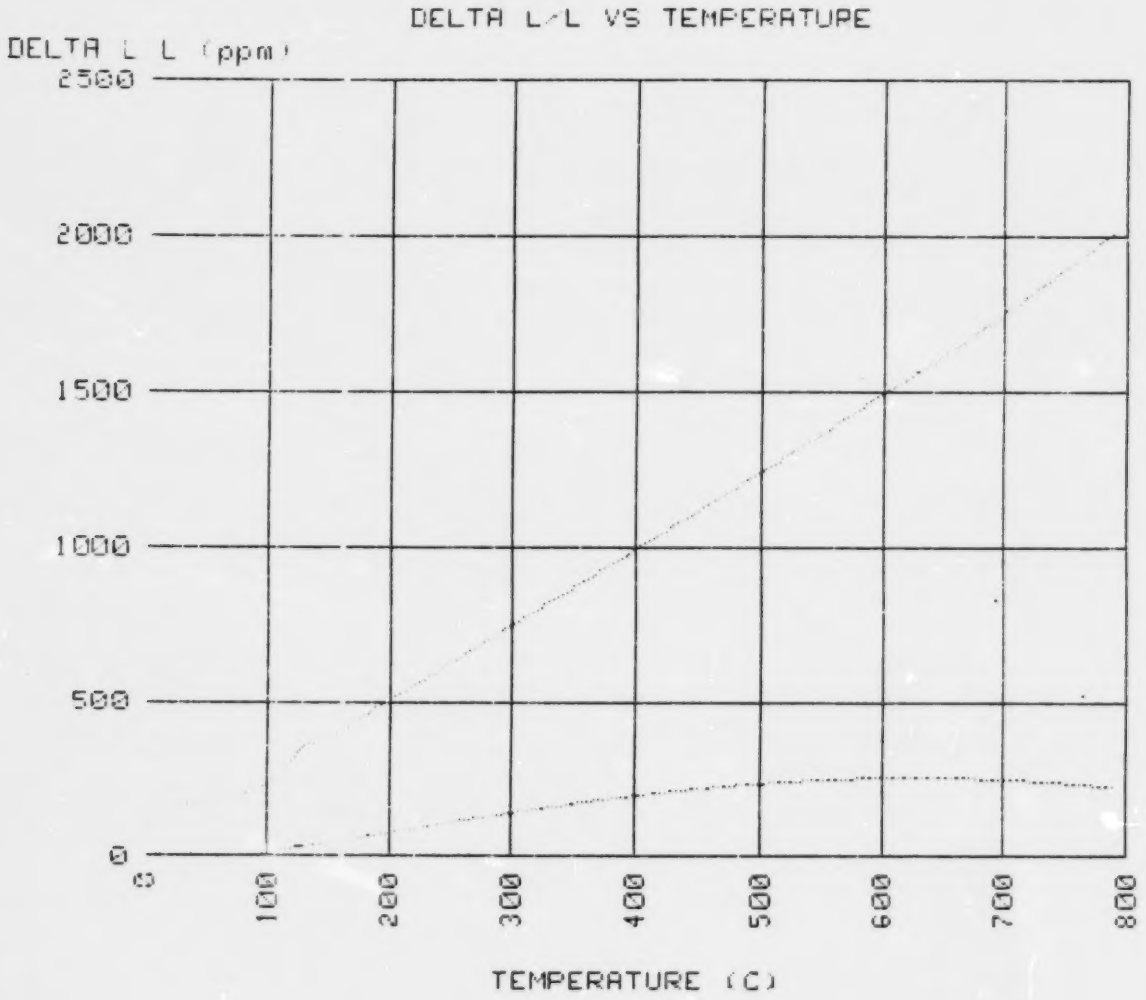


ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM 'CTE' VERSION 83/9/19 Glass & Ceramics Centre

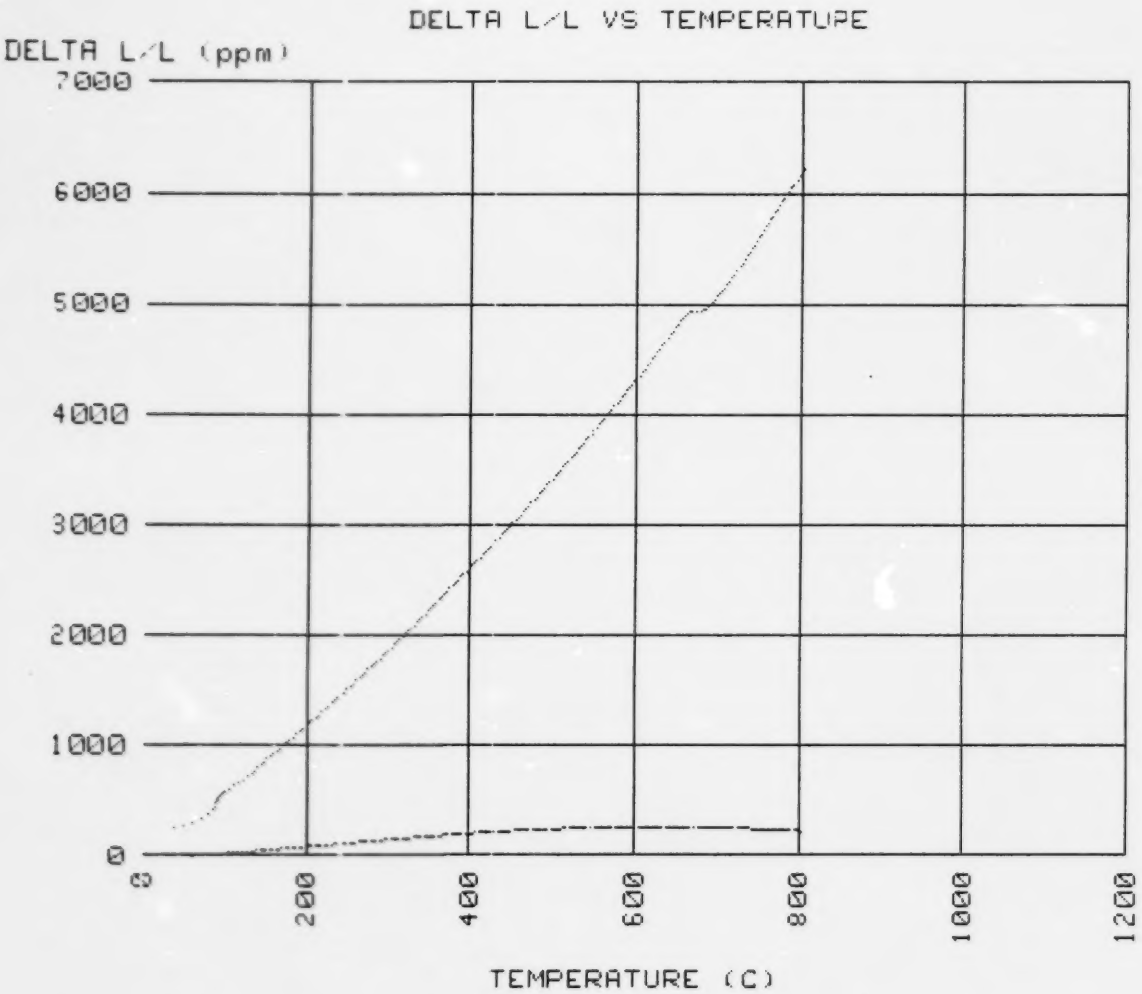
DATE AND TIME OF REPORT 09:07:08:20:32

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	615W
DATE OF RUN	08:07
RUN NUMBER	1
HP85 DATA FILE	615W
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.010
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	3.94 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	615W
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	DELTA L / L MEAS. ppm	DELTA L / L CORRECTED ppm	%NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29158	29122	232	0.00
6	0	0	0	0	0.00
11	0	0	0	0	0.00
16	81	29254	29258	367	4.51
21	93	29403	29414	521	12.82
26	112	29495	29517	631	5.78
31	136	29624	29661	769	5.73
36	155	29746	29789	899	6.94
41	176	29858	29912	1022	5.98
46	196	29967	30042	1151	6.40
51	215	30081	30169	1279	6.67
56	234	30196	30296	1407	6.67
61	253	30311	30423	1534	6.83
66	271	30427	30552	1662	6.99
71	289	30542	30678	1788	6.99
76	307	30657	30803	1913	7.10
81	324	30774	30930	2039	7.22
86	342	30888	31055	2165	7.23
91	358	31008	31184	2294	7.66
96	375	31125	31310	2420	7.50
101	392	31243	31437	2547	7.59
106	408	31365	31566	2675	7.88
111	425	31485	31694	2805	7.87
116	441	31608	31824	2934	7.90
121	457	31738	31952	3063	8.09
126	473	31856	32084	3195	8.24
131	489	31986	32220	3330	8.44
136	505	32115	32353	3464	8.53
141	521	32258	32493	3601	8.57
146	536	32382	32628	3739	8.79
151	552	32518	32767	3877	8.94

156	568	32659	32906	4017	8.90
161	583	32794	33045	4155	9.16
166	598	32930	33136	4295	8.88
171	613	33070	33329	4438	9.53
176	629	33225	33481	4592	10.11
181	644	33388	33644	4754	10.75
186	659	33528	33783	4889	8.80
191	674	33575	33828	4937	3.24
196	689	33626	33878	4993	3.76
201	704	33758	34007	5118	8.53
206	718	33909	34155	5265	10.05
211	733	34078	34321	5433	11.16
216	748	34248	34437	5597	11.40
221	762	34416	34651	5760	11.28
226	777	34582	34812	5920	10.87
231	791	34745	34970	6080	11.31
236	805	34906	35125	3723	-164.84

Date:09:07:08:20:32 Sample:615W Data File:615W



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM 'CTE' VERSION 83/9/19 Glass & Ceramics Centre

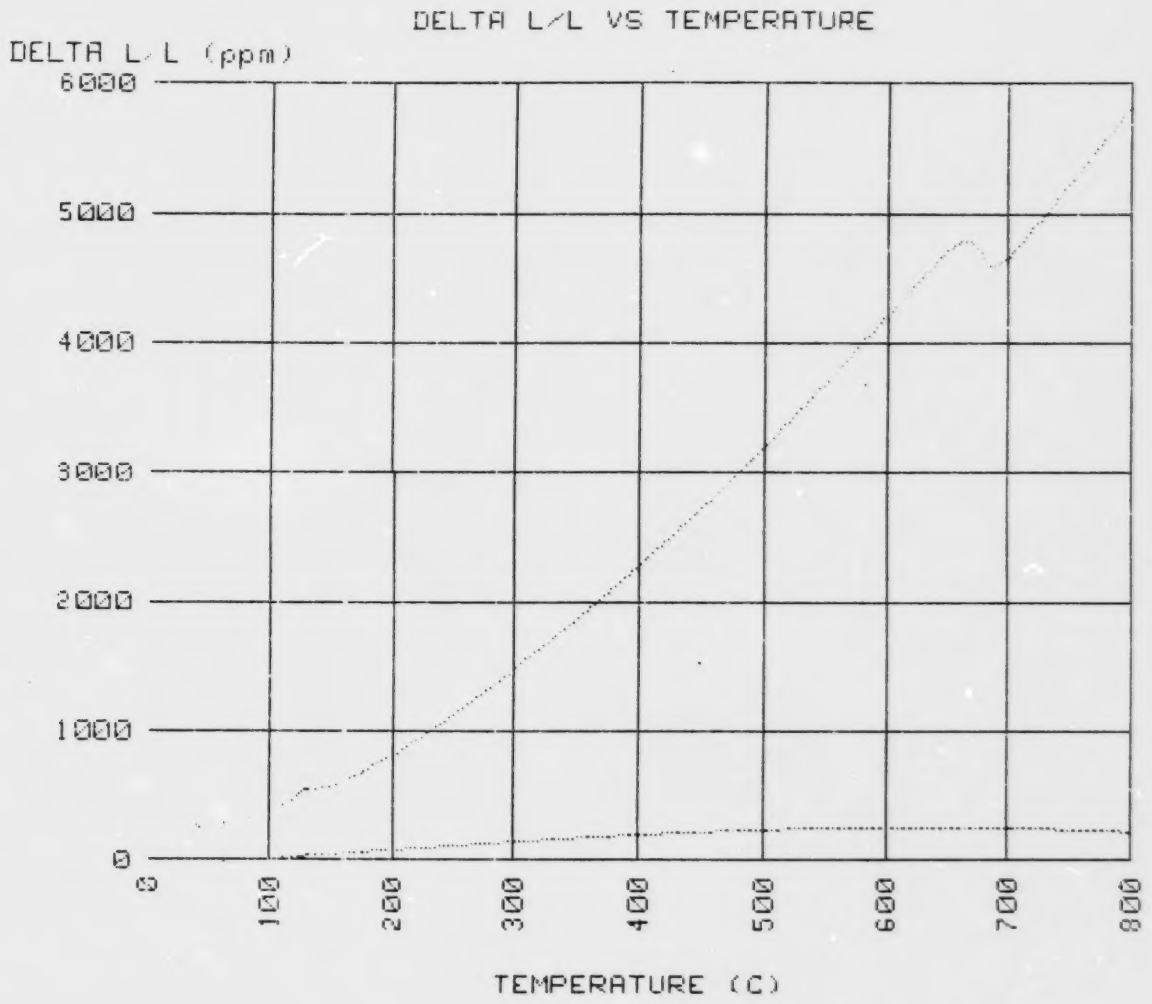
DATE AND TIME OF REPORT 09:04:12:55:31

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	616W/650 DEG C
DATE OF RUN	07:04
RUN NUMBER	1
HP85 DATA FILE	616W
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.0075
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	4 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	616W
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	DELTA L / L MEAS. ppm	DELTA L / L CORRECTED ppm	%NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29162	29126	216	0.00
6	0	0	0	0	0.00
11	0	0	0	0	0.00
16	0	0	0	0	0.00
21	85	29220	29226	328	3.88
26	125	29402	29431	511	4.57
31	130	29419	29452	544	5.70
36	155	29448	29497	590	1.86
41	177	29537	29600	691	4.59
46	196	29625	29700	791	5.37
51	216	29726	29815	905	5.60
56	235	29837	29939	1029	6.47
61	255	29949	30063	1154	6.53
66	273	30071	30196	1285	7.14
71	291	30189	30326	1417	7.13
76	309	30311	30459	1550	7.45
81	327	30434	30593	1684	7.53
86	344	30560	30728	1818	7.77
91	361	30688	30866	1956	8.09
96	378	30817	31004	2094	8.19
101	395	30949	31144	2235	8.40
106	411	31083	31286	2377	8.64
111	428	31220	31431	2520	8.72
116	444	31361	31578	2667	9.06
121	460	31505	31728	2817	9.39
126	476	31649	31878	2968	9.39
131	492	31795	32029	3119	9.61
136	508	31944	32183	3273	9.62
141	524	32095	32338	3428	9.95
146	539	32246	32493	3583	9.94
151	555	32402	32652	3741	10.13

156	570	32556	32808	3899	10.14
161	586	32714	32968	4059	10.38
166	601	32874	33129	4218	10.36
171	616	33036	33286	4376	10.47
176	632	33188	33444	4534	10.26
181	646	33346	33596	4684	10.12
186	661	33442	33696	4779	6.34
191	677	33363	33616	4702	-5.06
196	692	33260	33511	4611	-6.01
201	706	33380	33629	4721	7.59
206	721	33546	33792	4883	11.03
211	735	33719	33962	5053	11.91
216	750	33896	34135	5226	11.86
221	764	34071	34305	5397	11.78
226	779	34249	34479	5569	11.92
231	793	34426	34650	5738	11.32
236	808	34598	34816	5906	11.84

Date:09:04:12:55:31 Sample:616W/650 DEG C Data File:616W



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM 'CTE' VERSION 83/9/19 Glass & Ceramics Centre

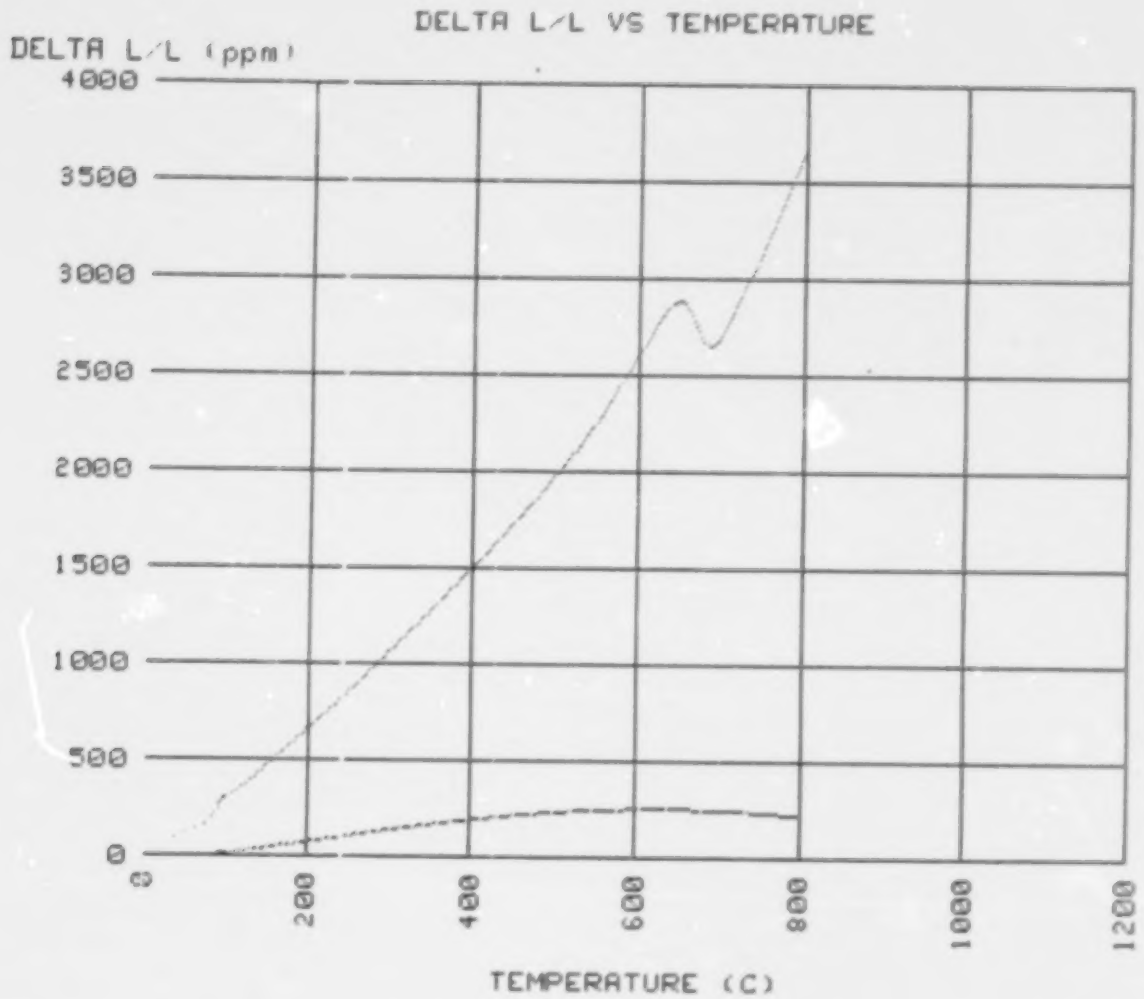
DATE AND TIME OF REPORT 16:07:09:29:10

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	628TMC
DATE OF RUN	14:07
RUN NUMBER	1
HP85 DATA FILE	628TMC
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.0065
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	3.94 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	628TMC
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	MEAS. ppm	DELTA L / L CORRECTED ppm	%NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29200	29165	70	0.00
6	0	0	0	0	0.00
11	0	0	0	0	0.00
16	74	29264	29264	170	2.28
21	95	29365	29377	279	5.28
26	109	29404	29424	333	3.84
31	136	29471	29508	413	3.02
36	155	29540	29589	494	4.20
41	175	29602	29664	569	3.64
46	196	29667	29742	646	3.85
51	215	29729	29817	722	3.89
56	234	29794	29894	799	4.03
61	253	29858	29970	875	4.10
66	271	29919	30043	950	4.15
71	289	29986	30122	1027	4.25
76	306	30050	30196	1102	4.29
81	324	30115	30272	1177	4.22
86	341	30178	30345	1250	4.25
91	358	30240	30416	1322	4.36
96	375	30304	30489	1396	4.32
101	391	30369	30562	1468	4.43
106	408	30436	30637	1542	4.46
111	424	30501	30710	1616	4.51
116	441	30571	30787	1692	4.73
121	457	30642	30864	1770	4.77
126	473	30712	30940	1847	4.86
131	489	30786	31021	1927	5.00
136	504	30865	31103	2009	5.23
141	520	30947	31190	2095	5.49
146	536	31033	31279	2185	5.72
151	551	31124	31373	2280	6.04

156	567	31224	31475	2381	6.43
161	582	31328	31582	2487	7.03
166	598	31439	31690	2595	6.93
171	613	31539	31795	2701	6.94
176	628	31642	31898	2804	6.86
181	643	31721	31977	2879	4.93
186	659	31702	31957	2857	-1.42
191	674	31574	31827	2733	-8.35
196	688	31495	31747	2661	-4.85
201	703	31581	31830	2736	5.13
206	718	31708	31954	2861	8.56
211	732	31847	32090	2996	9.29
216	747	31991	32230	3135	9.34
221	762	32137	32372	3277	9.92
226	776	32286	32516	3421	9.75
231	790	32432	32657	3563	9.93
236	805	32574	32794	2204	-95.21

Date:16:07:09:29:10 Sample:628TMC Data File:628TMC



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM CTE VERSION 83/9/19 Glass & Ceramics Centre

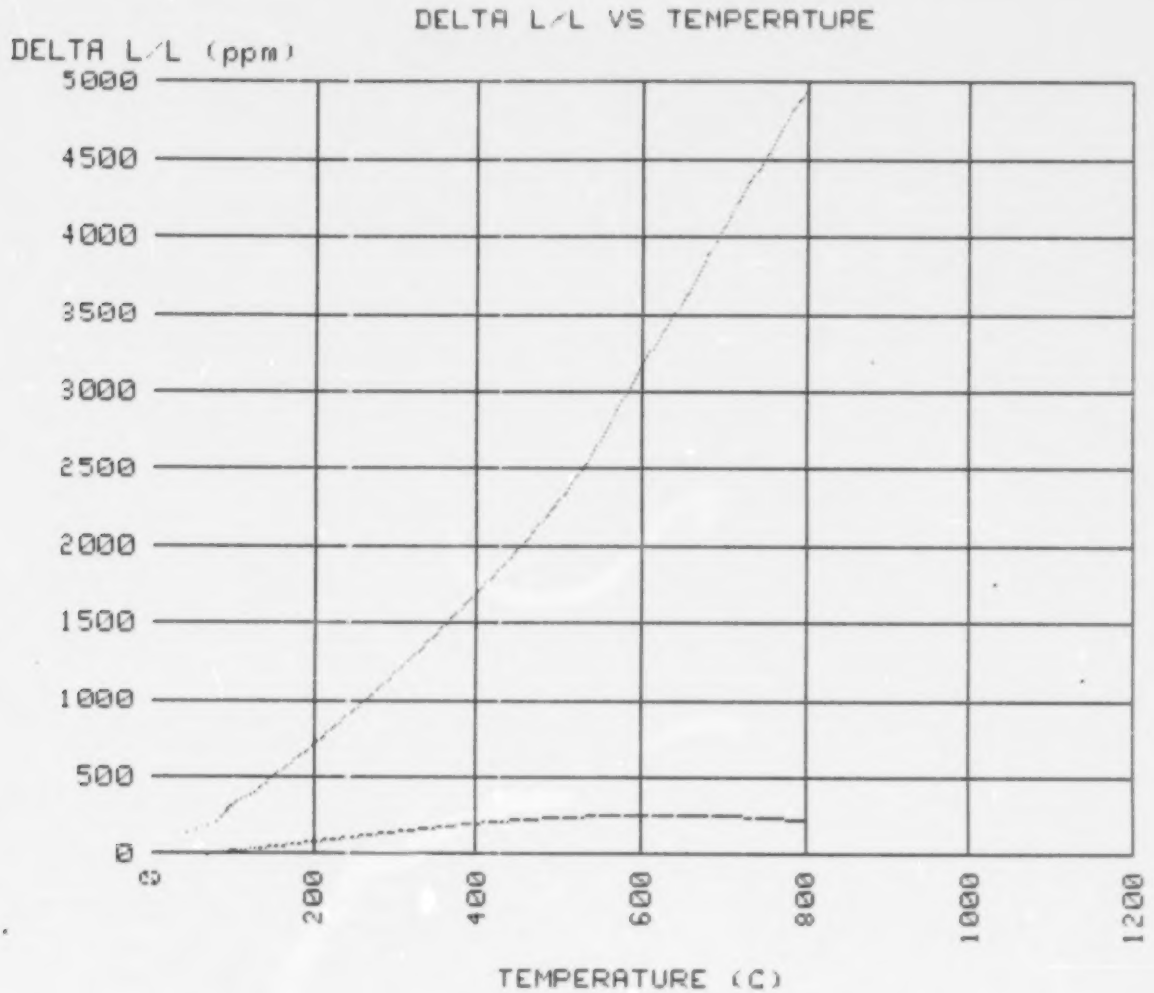
DATE AND TIME OF REPORT 17:07:09:30:54

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	628TF
DATE OF RUN	16:07
RUN NUMBER	1
HP85 DATA FILE	628TF
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.007
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	3.94 hrs.
STANDARD MATERIAL?	NONE
HP9345 DATA FILE NAME	628TF
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	MEAS. ppm	DELTA L / L CORRECTED ppm	&NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29214	29178	106	0.00
6	0	0	0	0	0.00
11	0	0	0	0	0.00
16	80	29277	29230	205	2.58
21	96	29354	29366	293	5.48
26	111	29397	29419	350	3.58
31	138	29474	29512	439	3.42
36	156	29546	29598	526	4.60
41	177	29616	29681	609	4.06
46	197	29694	29770	697	4.44
51	216	29766	29856	784	4.62
56	234	29842	29944	871	4.61
61	253	29915	30028	956	4.53
66	272	29991	30115	1043	4.75
71	289	30065	30200	1128	4.81
76	307	30136	30284	1213	4.93
81	324	30212	30369	1298	4.75
86	341	30289	30456	1384	5.11
91	358	30367	30543	1471	5.12
96	375	30445	30631	1559	5.25
101	392	30526	30721	1648	5.43
106	408	30606	30810	1738	5.48
111	424	30693	30901	1830	5.70
116	441	30782	30998	1926	5.79
121	456	30873	31095	2023	6.11
126	473	30965	31193	2123	6.16
131	488	31066	31293	2223	6.38
136	504	31163	31401	2329	6.76
141	520	31272	31515	2443	7.12
146	536	31393	31639	2568	8.07
151	551	31526	31777	2705	8.68

156	567	31672	31924	2850	9.44
161	582	31826	32073	3001	9.78
166	598	31961	32215	3145	9.19
171	613	32098	32354	3281	8.95
176	628	32236	32496	3413	8.77
181	643	32359	32614	3542	8.41
186	658	32489	32744	3673	9.06
191	673	32633	32887	3817	9.35
196	688	32786	33039	3967	9.90
201	703	32936	33179	4108	9.69
206	718	33066	33312	4241	8.95
211	733	33199	33442	4370	8.76
216	747	33328	33567	4495	8.72
221	761	33464	33699	4628	9.13
226	776	33609	33833	4760	8.97
231	790	33718	33942	4870	7.76
236	805	33816	34029	2966	-130.69

Date:17:07:09:30:54 Sample:628TF Data File:628TF



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM 'CTE' VERSION 83/9/19 Glass & Ceramics Centre

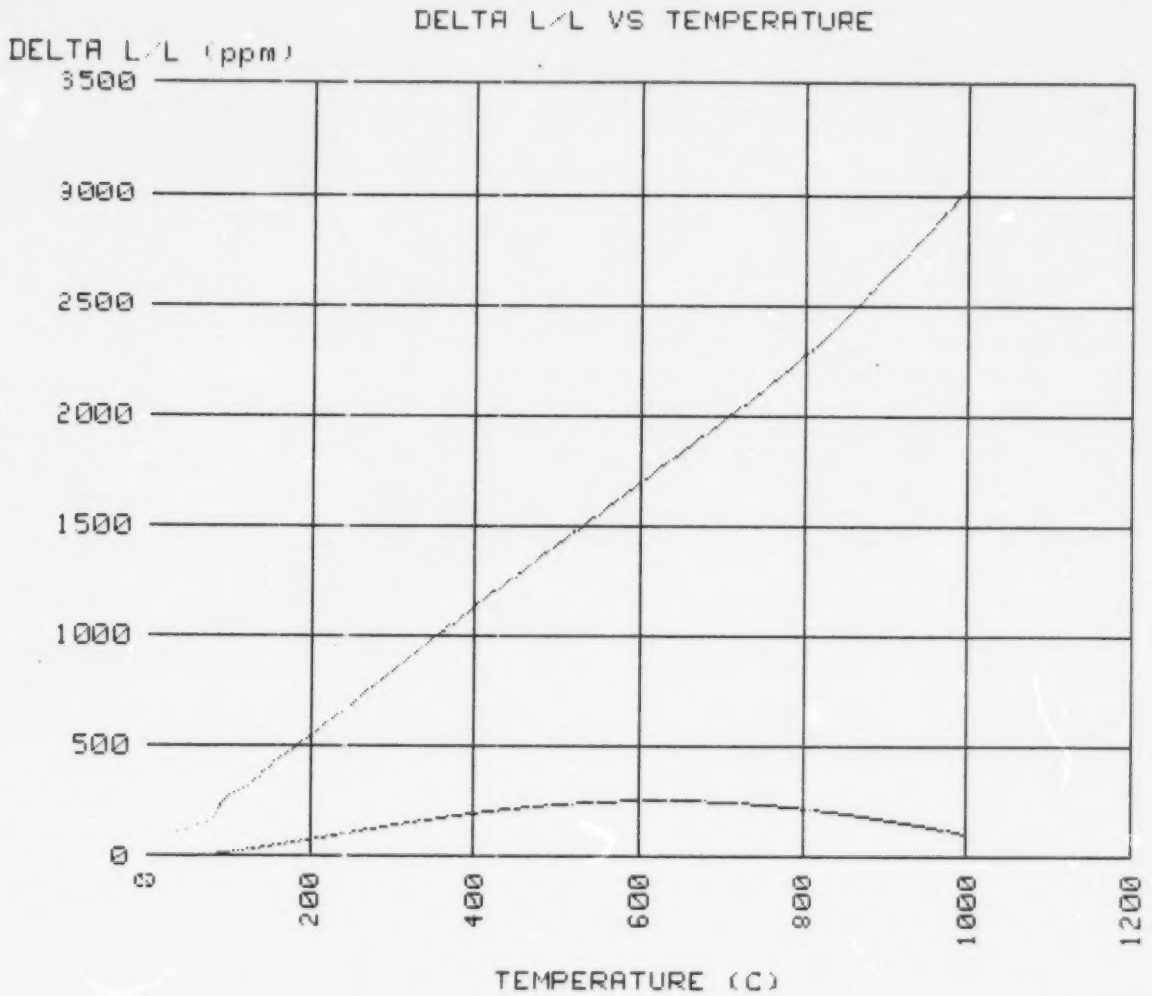
DATE AND TIME OF REPORT 09:07:16:21:57

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	629
DATE OF RUN	09:07
RUN NUMBER	1
HP85 DATA FILE	629
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.007
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	5.1 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	629
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	DELTA L / L MEAS. ppm	DELTA L / L CORRECTED ppm	%NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29234	29197	96	0.00
6	0	0	0	0	0.00
11	0	0	0	0	0.00
16	83	29275	29280	179	2.15
21	95	29342	29354	251	6.27
26	114	29377	29400	300	2.53
31	138	29426	29464	363	2.61
36	158	29476	29526	426	3.27
41	178	29521	29584	484	2.83
46	(198)	29567	29644	543	2.97
51	217	29613	29703	601	2.98
56	236	29656	29758	657	3.01
61	255	29697	29811	710	2.86
66	273	29739	29864	763	2.86
71	291	29780	29916	816	2.97
76	308	29821	29968	867	2.97
81	326	29862	30020	918	2.92
86	343	29902	30069	968	2.95
91	360	29941	30118	1017	2.87
96	376	29979	30164	1065	2.92
101	393	30020	30214	1114	2.88
106	409	30059	30261	1161	2.93
111	425	30099	30308	1208	2.88
116	442	30138	30355	1254	2.83
121	458	30178	30400	1300	2.86
126	474	30217	30446	1345	2.86
131	489	30257	30490	1389	2.80
136	505	30294	30533	1433	2.73
141	520	30334	30576	1476	2.86
146	537	30373	30620	1520	2.72
151	552	30411	30660	1561	2.74

156	567	30452	30704	1604	2.75
161	583	30495	30749	1648	2.80
166	598	30538	30793	1692	2.97
171	613	30578	30833	1733	2.65
176	629	30620	30877	1777	2.85
181	644	30663	30919	1819	2.79
186	659	30705	30960	1860	2.77
191	674	30749	31003	1902	2.83
196	689	30792	31044	1944	2.80
201	703	30837	31086	1986	2.87
206	718	30883	31129	2028	2.83
211	733	30929	31172	2071	2.86
216	747	30974	31213	2112	2.91
221	762	31022	31257	2156	2.98
226	776	31068	31298	2198	2.95
231	790	31118	31343	2242	3.04
236	805	31168	31387	2287	3.09
241	819	31219	31432	2332	3.21
246	834	31276	31482	2382	3.45
251	847	31334	31534	2433	3.78
256	862	31393	31585	2485	3.50
261	876	31454	31639	2540	3.85
266	890	31516	31694	2595	4.07
271	904	31580	31749	2648	3.79
276	918	31645	31805	2703	3.94
281	931	31705	31857	2757	4.12
286	945	31770	31913	2813	3.87
291	959	31837	31971	2869	3.97
296	972	31900	32025	2923	4.12
301	986	31961	32076	2975	3.79
306	1000	32019	32124	1808	-84.15

Date:09:07:16:21:57 Sample:629 Data File:629



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM 'CTE' VERSION 83/9 19 Glass & Ceramics Centre

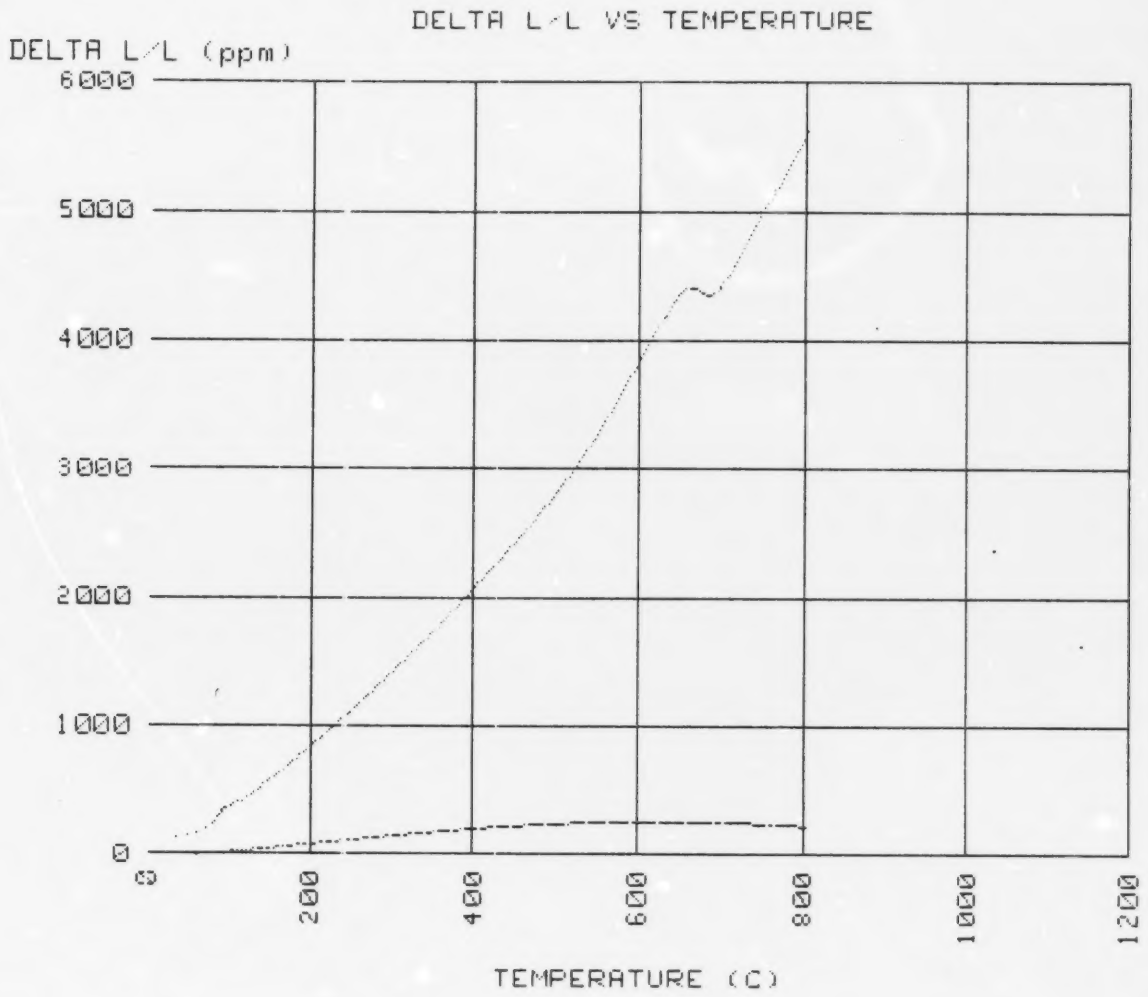
DATE AND TIME OF REPORT 10:07:15:23:26

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	630 TKM0
DATE OF RUN	10:07
RUN NUMBER	1
HP85 DATA FILE	30TKM0
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	1.998
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	3.94 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	30TKM0
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	DELTA L / L MEAS. ppm	DELTA L / L CORRECTED ppm	%NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29369	29334	102	0.00
6	0	0	0	0	0.00
11	0	0	0	0	0.00
16	80	29459	29459	225	2.81
21	93	29557	29568	335	8.36
26	111	29609	29630	401	3.61
31	136	29692	29728	496	3.87
36	155	29783	29832	599	5.39
41	176	29871	29933	702	4.94
46	198	29966	30041	810	5.40
51	215	30064	30152	920	5.67
56	234	30159	30259	1028	5.65
61	253	30253	30366	1135	5.68
66	272	30355	30480	1247	6.09
71	290	30453	30589	1357	6.12
76	307	30552	30698	1466	6.21
81	325	30652	30809	1577	6.29
86	342	30752	30918	1687	6.40
91	359	30850	31026	1795	6.24
96	376	30951	31137	1905	6.67
101	393	31055	31249	2017	6.64
106	409	31160	31362	2131	6.88
111	425	31269	31478	2247	7.17
116	442	31381	31597	2364	7.19
121	458	31493	31715	2485	7.38
126	474	31612	31840	2608	7.91
131	490	31730	31964	2734	7.78
136	506	31850	32095	2864	8.20
141	521	31989	32232	3000	8.69
146	537	32130	32377	3146	9.31
151	553	32287	32537	3305	10.03

156	568	32454	32706	3475	10.88
161	584	32628	32882	3651	11.40
166	599	32801	33056	3824	11.40
171	615	32973	33229	3998	11.12
176	630	33144	33400	4168	11.10
181	645	33295	33551	4317	10.03
186	660	33382	33636	4399	5.42
191	675	33351	33604	4375	-1.60
196	690	33345	33597	4370	-.33
201	705	33461	33710	4482	7.72
206	720	33633	33879	4648	11.30
211	734	33811	34053	4821	11.69
216	749	33985	34224	4992	12.07
221	763	34159	34393	5162	11.71
226	778	34336	34559	5327	11.14
231	792	34496	34723	5491	11.39
236	807	34669	34838	3374	-146.07

Date:10:07:15:23:26 Sample:630 TKM0 Data File:30TKM0



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM 'CTE' VERSION 83/9/19 Glass & Ceramics Centre

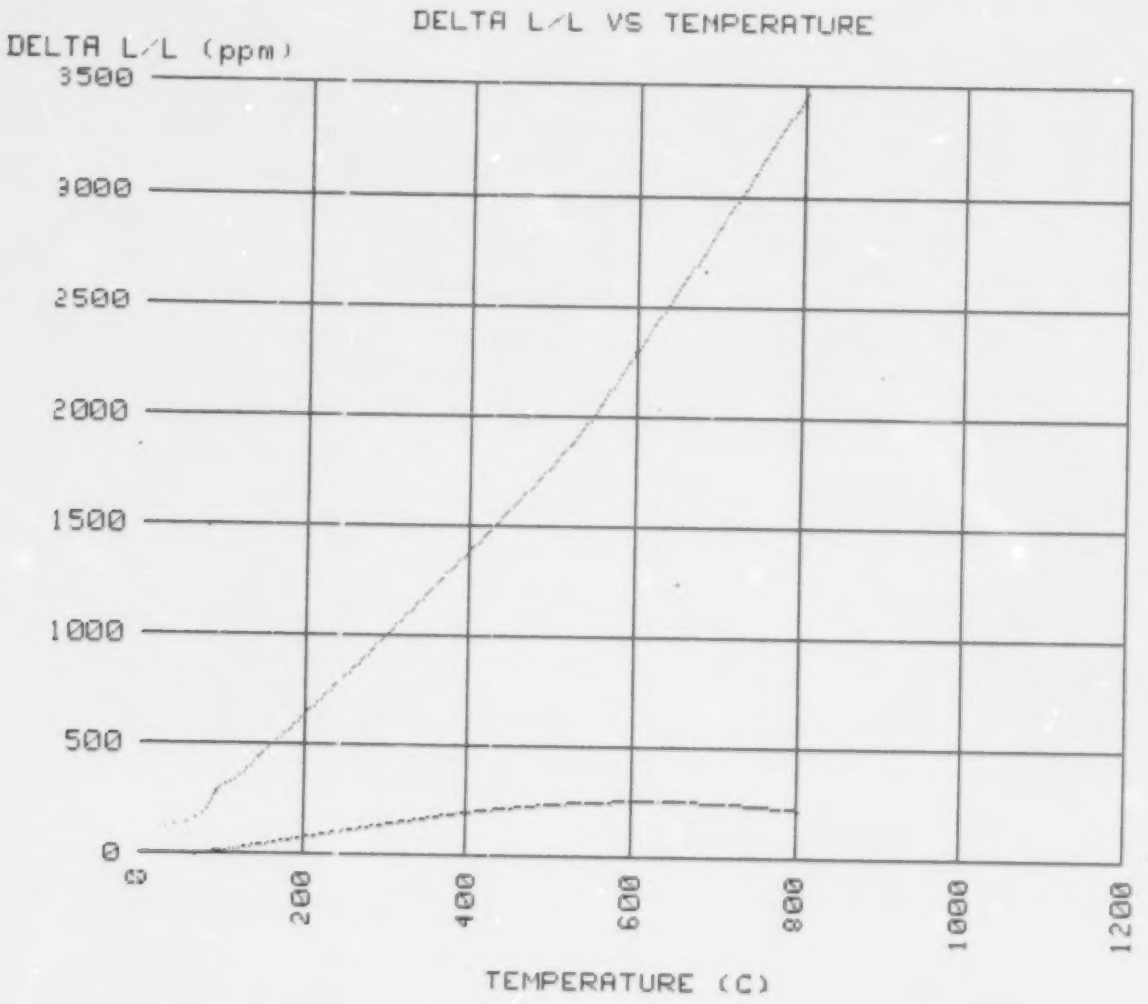
DATE AND TIME OF REPORT 14:07:08:18:18

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	630TKM1
DATE OF RUN	10:07
RUN NUMBER	1
HP85 DATA FILE	30TKM1
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.000
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	3.94 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	30TKM1
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	MEAS. ppm	DELTA L / L CORRECTED ppm	%NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29328	29292	103	0.00
6	0	0	0	0	0.00
11	0	0	0	0	0.00
16	78	29374	29376	186	2.40
21	94	29455	29466	275	5.58
26	111	29497	29518	330	3.21
31	136	29557	29593	404	2.94
36	155	29619	29668	478	3.79
41	176	29676	29738	548	3.46
46	196	29736	29811	621	3.57
51	215	29796	29884	693	3.75
56	235	29853	29954	763	3.64
61	253	29908	30021	831	3.67
66	272	29967	30091	901	3.78
71	290	30022	30157	968	3.69
76	307	30079	30225	1035	3.83
81	325	30134	30291	1101	3.76
86	342	30190	30357	1167	3.85
91	359	30244	30420	1230	3.73
96	376	30301	30486	1295	3.82
101	392	30354	30548	1359	3.87
106	409	30409	30611	1421	3.77
111	425	30464	30673	1484	3.82
116	441	30521	30737	1547	3.95
121	458	30578	30800	1611	3.93
126	474	30636	30865	1675	4.00
131	489	30695	30929	1739	4.04
136	505	30757	30995	1806	4.22
141	521	30821	31063	1874	4.38
146	537	30891	31137	1949	4.74
151	552	30969	31218	2029	5.12

156	568	31053	31305	2115	5.54
161	583	31141	31395	2205	5.82
166	598	31227	31482	2291	5.67
171	614	31316	31565	2375	5.47
176	629	31398	31648	2459	5.50
181	644	31477	31732	2543	5.50
186	659	31563	31818	2627	5.57
191	674	31647	31901	2711	5.63
196	689	31737	31988	2798	5.80
201	704	31824	32074	2884	5.88
206	719	31914	32160	2972	5.88
211	733	32005	32248	3059	5.98
216	748	32098	32337	3146	5.94
221	763	32186	32421	3232	5.90
226	777	32276	32505	3315	5.79
231	791	32360	32585	3395	5.68
236	806	32448	32666	2077	-88.72

Date:14:07:03:18:18 Sample:630TKM1 Data File:30TKM1



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM '*CTE*' VERSION 83/9/19 Glass & Ceramics Centre

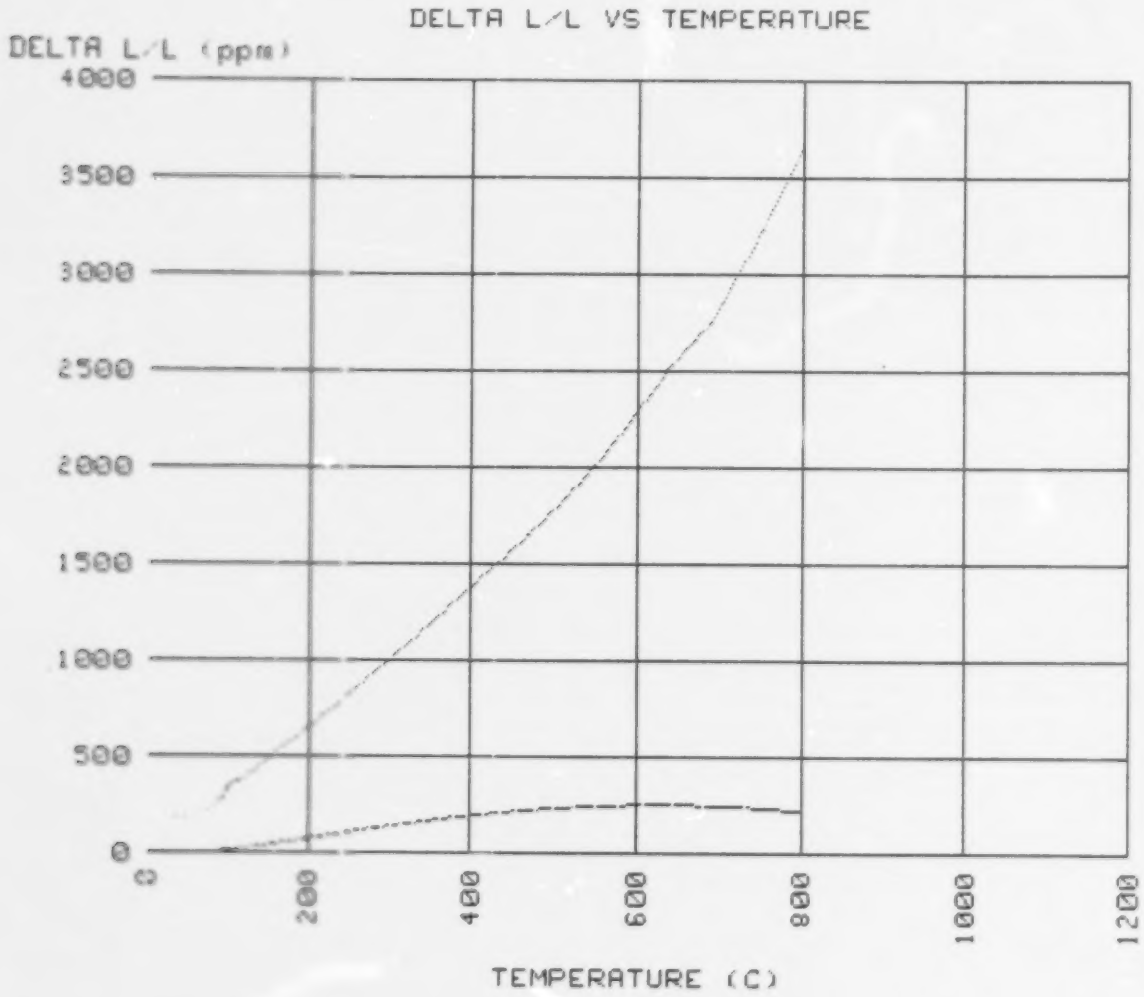
DATE AND TIME OF REPORT 14:07:08:06:00

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	630TKM2
DATE OF RUN	11:07
RUN NUMBER	1
HP85 DATA FILE	30TKM2
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.007
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	3.94 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	30TKM2
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	MEAS. ppm	DELTA L / L CORRECTED ppm	%NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29195	29159	165	0.00
6	0	0	0	0	0.00
11	0	0	0	0	0.00
16	74	29226	29220	228	3.06
21	98	29296	29311	314	3.70
26	110	29344	29365	371	4.53
31	136	29395	29432	437	2.54
36	156	29454	29503	508	3.66
41	176	29505	29567	574	3.32
46	196	29562	29637	642	3.37
51	215	29615	29703	708	3.42
56	234	29666	29768	775	3.51
61	253	29721	29834	840	3.53
66	271	29776	29900	906	3.62
71	289	29829	29965	971	3.62
76	306	29884	30030	1035	3.65
81	324	29936	30094	1100	3.69
86	341	29992	30159	1164	3.72
91	358	30047	30223	1227	3.76
96	375	30095	30284	1290	3.72
101	391	30154	30347	1353	3.82
106	408	30210	30412	1417	3.89
111	424	30265	30474	1481	3.86
116	440	30322	30538	1545	3.98
121	457	30386	30602	1609	3.97
126	472	30442	30670	1675	4.15
131	488	30502	30735	1742	4.22
136	504	30567	30805	1812	4.40
141	520	30634	30876	1883	4.57
146	536	30705	30950	1957	4.68
151	551	30786	31029	2035	4.98

156	567	30861	31112	2117	5.33
161	582	30941	31195	2200	5.32
166	597	31024	31279	2285	5.58
171	613	3110[illegible]	31365	2372	5.63
176	628	3119[illegible]	31451	2458	5.65
181	643	3128[illegible]	31539	2545	5.72
186	658	3136[illegible]	31615	2620	4.94
191	674	3142[illegible]	31679	2685	4.37
196	688	3150[illegible]	31759	2766	5.38
201	703	3161[illegible]	31862	2869	7.09
206	718	31731	31977	2983	7.76
211	733	3185[illegible]	32095	3101	7.91
216	747	3197[illegible]	32215	3220	8.16
221	762	3209[illegible]	32331	3338	8.18
226	776	32221	32451	3457	8.23
231	791	3234[illegible]	32570	3575	8.12

Date:14:07:08:06:00 Sample:630TKM2 Data File:30TKM2



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM 'CTE' VERSION 83/9/19 Glass & Ceramics Centre

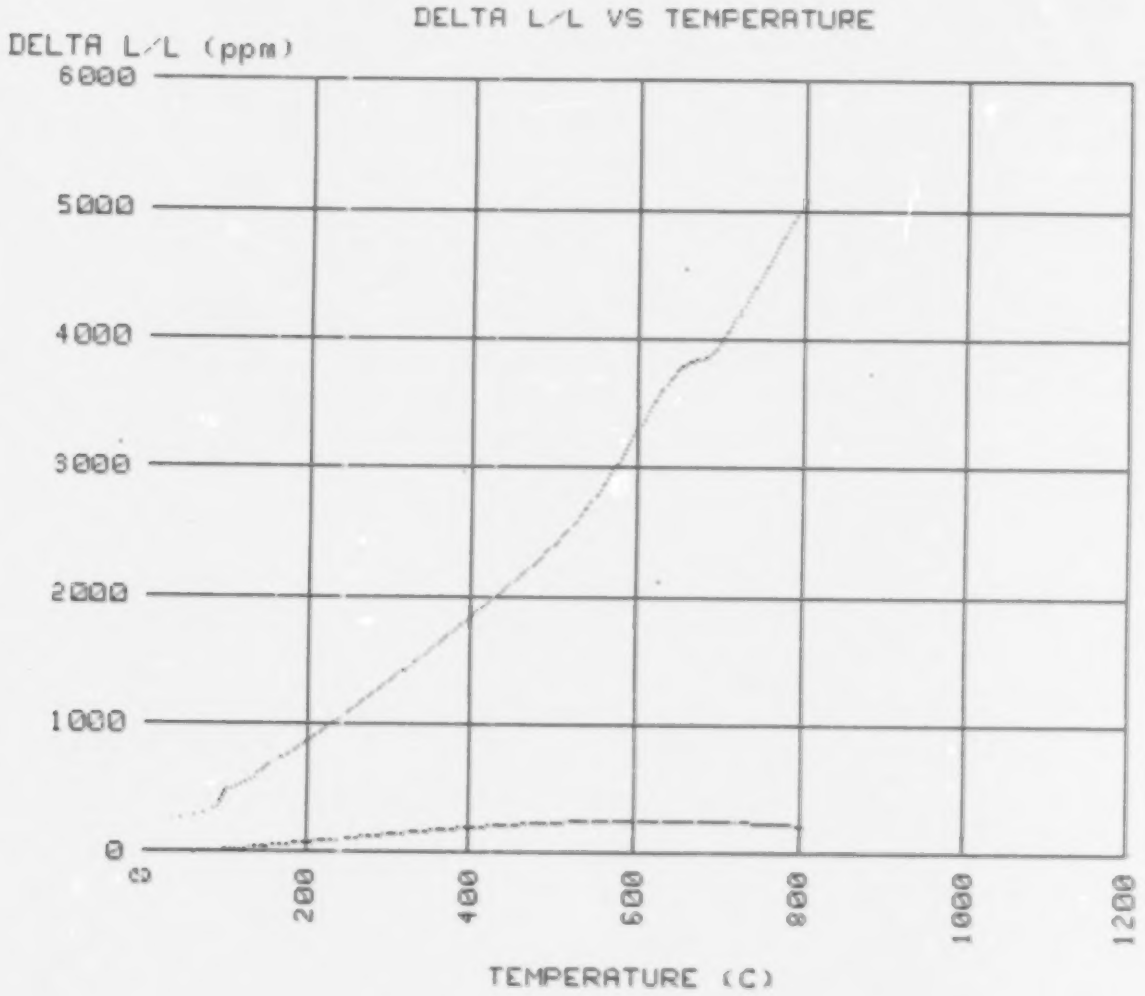
DATE AND TIME OF REPORT 16:07:09:25:37

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	630TKM3
DATE OF RUN	15:07
RUN NUMBER	1
HP85 DATA FILE	30TKM3
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	1.996
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	3.94 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	30TKM3
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	MEAS. ppm	DELTA L / L CORRECTED ppm	%NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29368	29332	238	0.00
6	0	0	0	0	0.00
11	0	0	0	0	0.00
16	86	29421	29428	335	3.88
21	98	29526	29540	444	9.12
26	114	29583	29606	515	4.49
31	140	29664	29704	609	3.63
36	158	29746	29791	698	4.80
41	179	29809	29874	781	3.97
46	199	29883	29961	867	4.43
51	218	29956	30045	953	4.57
56	236	30028	30130	1037	4.58
61	254	30103	30216	1122	4.61
66	273	30173	30298	1206	4.64
71	291	30249	30386	1292	4.75
76	308	30323	30470	1376	4.94
81	325	30398	30555	1461	4.88
86	342	30473	30641	1546	5.01
91	359	30548	30724	1631	5.00
96	376	30624	30809	1715	5.02
101	392	30700	30893	1800	5.09
106	409	30775	30977	1884	5.17
111	425	30857	31066	1972	5.26
116	441	30934	31150	2058	5.55
121	458	31020	31243	2149	5.42
126	474	31105	31333	2240	5.77
131	490	31195	31428	2335	5.96
136	505	31293	31531	2437	6.67
141	521	31397	31639	2546	6.89
146	536	31514	31760	2667	7.73
151	552	31645	31894	2802	8.54

156	568	31793	32045	2951	9.69
161	583	31956	32209	3115	10.58
166	598	32121	32376	3281	10.83
171	613	32283	32539	3443	10.82
176	629	32433	32689	3595	9.80
181	644	32568	32824	3726	8.57
186	659	32647	32902	3807	5.39
191	674	32684	32937	3845	2.57
196	689	32739	32990	3900	3.63
201	704	32861	33111	4018	8.08
206	718	33015	33261	4169	10.27
211	733	33179	33422	4328	10.86
216	748	33344	33583	4488	10.91
221	762	33507	33741	4647	10.92
226	777	33672	33902	4809.	11.28
231	791	33833	34057	4963	10.63
236	806	33993	34212	3052	-131.18

Date:16:07:09:25:37 Sample:630TKM3 Data File:30TKM3



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM '/CTE/' VERSION 83/9/19 Glass & Ceramics Centre

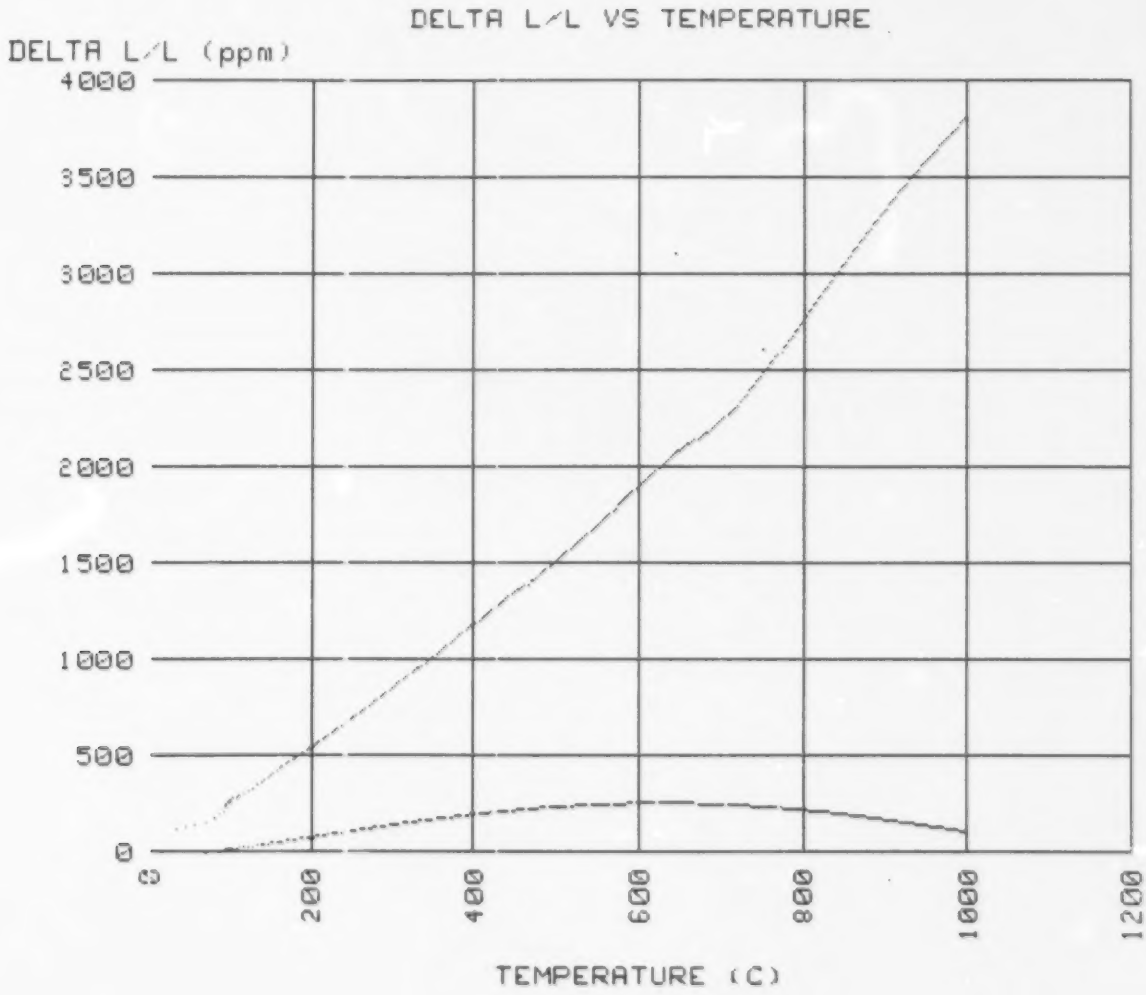
DATE AND TIME OF REPORT 03:11:15:30:17

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	636 TKM6
DATE OF RUN	30:10
RUN NUMBER	1
HP85 DATA FILE	636TM6
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.004
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	5.1 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	636TM6
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	MEAS. ppm	DELTA L / L CORRECTED ppm	&NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29262	29227	93	0.00
6	0	0	0	0	0.00
11	0	0	0	0	0.00
16	80	29309	29312	178	2.23
21	98	29378	29391	254	4.29
26	112	29408	29431	298	2.99
31	138	29457	29495	361	2.40
36	158	29503	29553	421	3.12
41	178	29546	29609	477	2.75
46	199	29594	29671	537	2.95
51	218	29639	29728	595	3.08
56	236	29687	29789	655	3.13
61	255	29733	29847	713	3.18
66	273	29778	29903	771	3.16
71	291	29824	29961	828	3.15
76	308	29871	30018	884	3.28
81	326	29915	30073	940	3.16
86	343	29963	30131	997	3.35
91	360	30008	30185	1052	3.27
96	377	30055	30240	1107	3.25
101	393	30101	30295	1162	3.37
106	410	30149	30351	1217	3.34
111	426	30195	30405	1272	3.33
116	442	30244	30460	1327	3.46
121	458	30292	30514	1379	3.21
126	474	30331	30560,	1426	2.96
131	490	30379	30613	1480	3.35
136	506	30429	30668	1535	3.50
141	522	30484	30727	1594	3.68
146	537	30539	30785	1652	3.78
151	553	30598	30847	1713	3.95

156	568	30658	30910	1776	4.02
161	584	30726	30973	1839	3.94
166	599	30776	31031	1899	4.05
171	615	30838	31094	1961	4.00
176	630	30897	31153	2019	3.90
181	645	30948	31204	2072	3.41
186	660	30995	31249	2115	2.97
191	675	31036	31289	2157	2.73
196	690	31084	31335	2201	2.98
201	704	31139	31388	2256	3.70
206	719	31209	31456	2323	4.65
211	734	31287	31529	2397	4.98
216	748	31367	31606	2474	5.30
221	763	31452	31686	2552	5.36
226	777	31539	31769	2635	5.77
231	792	31627	31851	2719	5.85
236	806	31718	31937	2804	5.86
241	820	31809	32022	2888	6.04
246	834	31897	32103	2970	5.77
251	849	31984	32184	3050	5.47
256	863	32072	32264	3131	5.83
261	877	32166	32344	3210	5.51
266	891	32246	32422	3288	5.65
271	904	32326	32495	3361	5.43
276	919	32407	32567	3433	5.04
281	932	32486	32638	3504	5.10
286	946	32562	32705	3572	5.17
291	960	32636	32769	3636	4.53
296	973	32709	32834	3700	4.68
301	987	32783	32898	3764	4.62
306	1000	32861	32966	2291	-111.78

Date:03:11:15:30:17 Sample:636 TKM6 Data File:636TM6



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM 'CTE' VERSION 83/9/19 Glass & Ceramics Centre

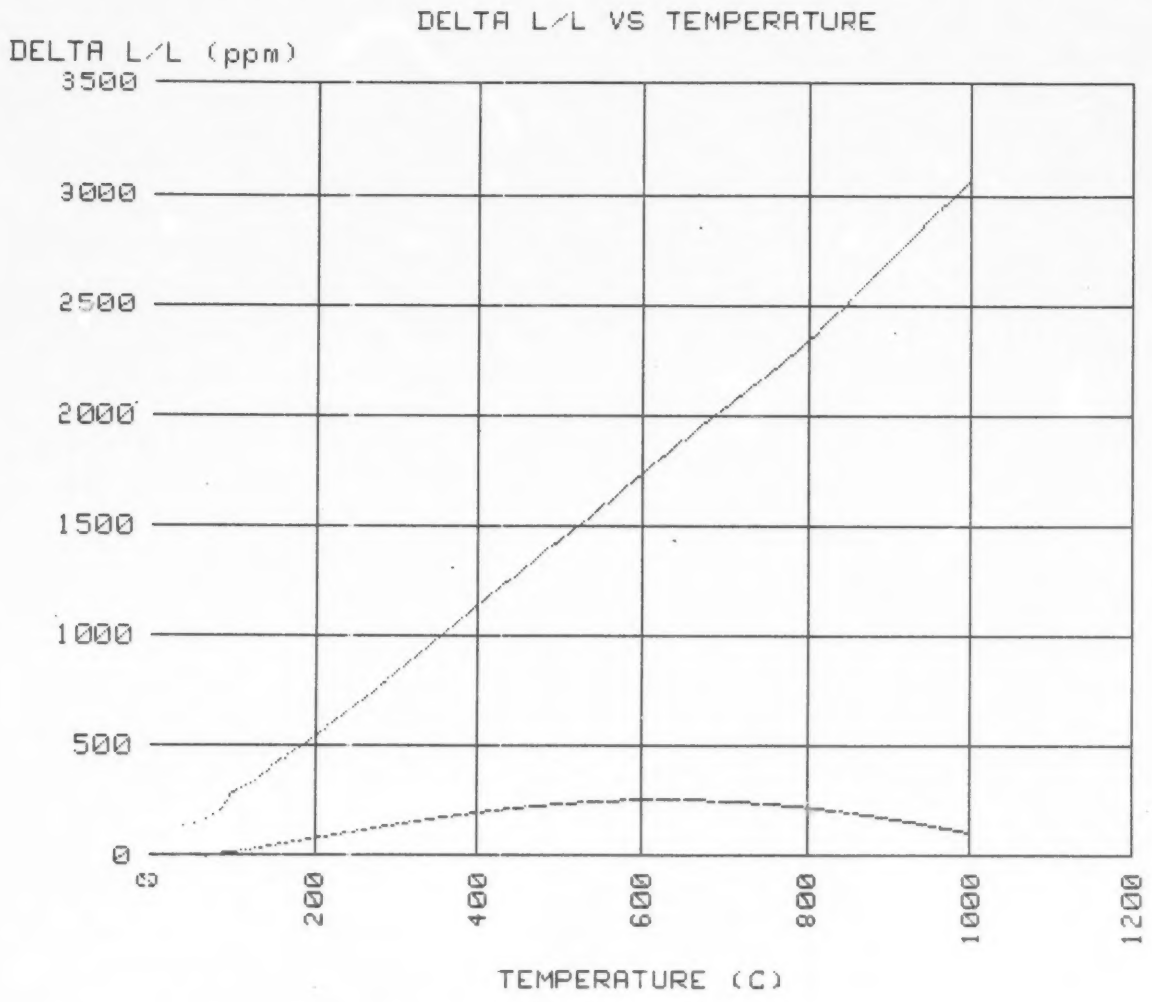
DATE AND TIME OF REPORT 12:11:09:36:39

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	638/1000 DEG C/1H
DATE OF RUN	11:11
RUN NUMBER	1
HP85 DATA FILE	638
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.0075
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	5.1 hrs.
STANDARD MATERIAL?	N
HP9845 DATA FILE NAME	638
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	DELTA L / L MEAS. ppm	CORRECTED ppm	&NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	2923€	29195	107	0.00
6	0	€	0	0	0.00
11	0	€	0	0	0.00
16	80	2926€	29271	184	2.31
21	96	2934€	29352	263	4.74
26	111	2937	29396	309	3.10
31	137	2941	29456	369	2.28
36	156	2946	29515	426	3.05
41	176	2950	29567	480	2.68
46	196	2954	29625	536	2.82
51	215	2959€	29678	590	2.80
56	234	2962€	29728	643	2.82
61	252	2967	29785	697	2.94
66	271	29714	29838	750	2.95
71	288	2975	29890	803	2.96
76	306	2979€	29944	856	3.02
81	323	2983	29995	908	3.04
86	340	2988€	30046	959	2.92
91	357	2992	30099	1011	3.07
96	374	29964	30149	1061	3.06
101	391	3000€	30199	1110	2.93

111	423	30090	30298	1211	2.96
116	439	30131	30346	1259	3.02
121	456	30174	30395	1308	3.05
126	471	30215	30442	1356	3.01
131	487	30258	30491	1403	2.94
136	503	30299	30537	1449	2.92
141	519	30340	30582	1495	2.88
146	535	30383	30629	1541	2.92
151	551	30426	30675	1587	2.97
156	566	30469	30720	1633	2.97
161	582	30513	30767	1680	3.01
166	597	30560	30815	1727	3.13
171	612	30606	30862	1774	3.00
176	627	30651	30907	1820	3.00
181	643	30695	30951	1864	2.95
186	658	30743	30998	1909	2.97
191	673	30788	31042	1953	2.97
196	688	30832	31084	1998	2.97
201	703	30879	31128	2042	2.95
206	717	30927	31173	2086	3.01
211	732	30971	31215	2128	2.87
216	747	31021	31260	2172	2.97
221	761	31069	31304	2216	3.06
226	775	31117	31348	2260	3.05
231	790	31165	31390	2303	2.93
236	804	31217	31436	2349	3.31
241	819	31277	31490	2402	3.62
246	833	31338	31546	2457	3.96
251	847	31398	31599	2511	3.67
256	861	31460	31653	2566	3.86
261	875	31520	31706	2618	3.80
266	889	31579	31756	2669	3.64
271	903	31640	31810	2721	3.67
276	917	31699	31860	2772	3.74
281	931	31759	31911	2824	3.76
286	944	31815	31959	2873	3.57
291	958	31872	32006	2921	3.49
296	972	31930	32055	2969	3.44
301	986	31989	32104	3018	3.53
306	999	32045	32151	1832	-91.95

Date:12:11:09:36:39 Sample:638/1000 DEG C/1H Data File:638



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM 'CTE' VERSION 83/9/19 Glass & Ceramics Centre

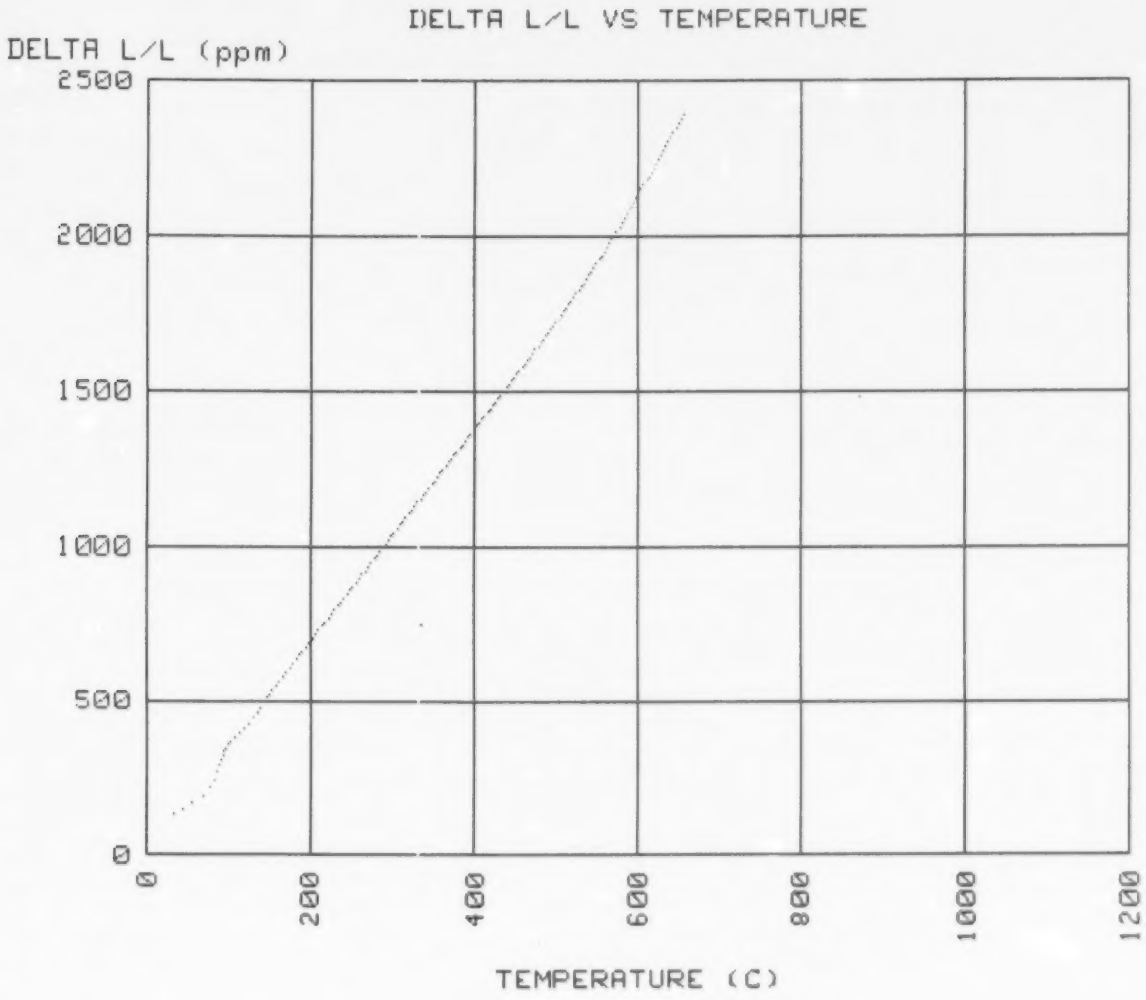
DATE AND TIME OF REPORT 06:02:11:33:38

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	640TKM6
DATE OF RUN	05:02
RUN NUMBER	1
HP85 DATA FILE	640TM6
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.006
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	3.1 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	640TM6
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	DELTA L / L MEAS. ppm	DELTA L / L CORRECTED ppm	&NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29206	28948	99	0.00
6	0	0	0	0	0.00
11	0	0	0	0	0.00
16	78	29259	29070	220	2.81
21	94	29350	29173	321	6.46
26	110	29396	29231	382	3.89
31	136	29456	29309	460	2.99
36	154	29520	29385	536	4.02
41	175	29575	29453	603	3.30
46	195	29633	29523	674	3.49
51	214	29690	29591	741	3.47
56	233	29745	29655	806	3.42
61	252	29800	29719	870	3.46
66	270	29855	29782	934	3.47
71	288	29910	29845	996	3.50
76	306	29963	29905	1056	3.37
81	323	30018	29966	1117	3.46
86	341	30071	30025	1176	3.41
91	358	30126	30085	1236	3.50
96	375	30179	30143	1294	3.50
101	391	30234	30201	1352	3.47
106	408	30287	30258	1410	3.53
111	424	30342	30316	1467	3.44
116	440	30395	30372	1524	3.57
121	457	30449	30427	1578	3.34
126	473	30504	30483	1634	3.47
131	489	30558	30539	1690	3.44
136	505	30613	30595	1747	3.61
141	520	30672	30653	1805	3.77
146	536	30732	30713	1864	3.81
151	551	30794	30774	1926	3.98

156	567	30861	30840	1991	4.16
161	582	30933	30910	2060	4.37
166	598	30998	30973	2124	4.28
171	613	31070	31043	2194	4.55
176	628	31142	31112	2263	4.61
181	643	31218	31184	2336	4.78
186	658	31293	31255	1435	-59.75

Date:06:02:11:33:38 Sample:640TKM6 Data File:640TM6



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM 'CTE' VERSION 83/9/19 Glass & Ceramics Centre

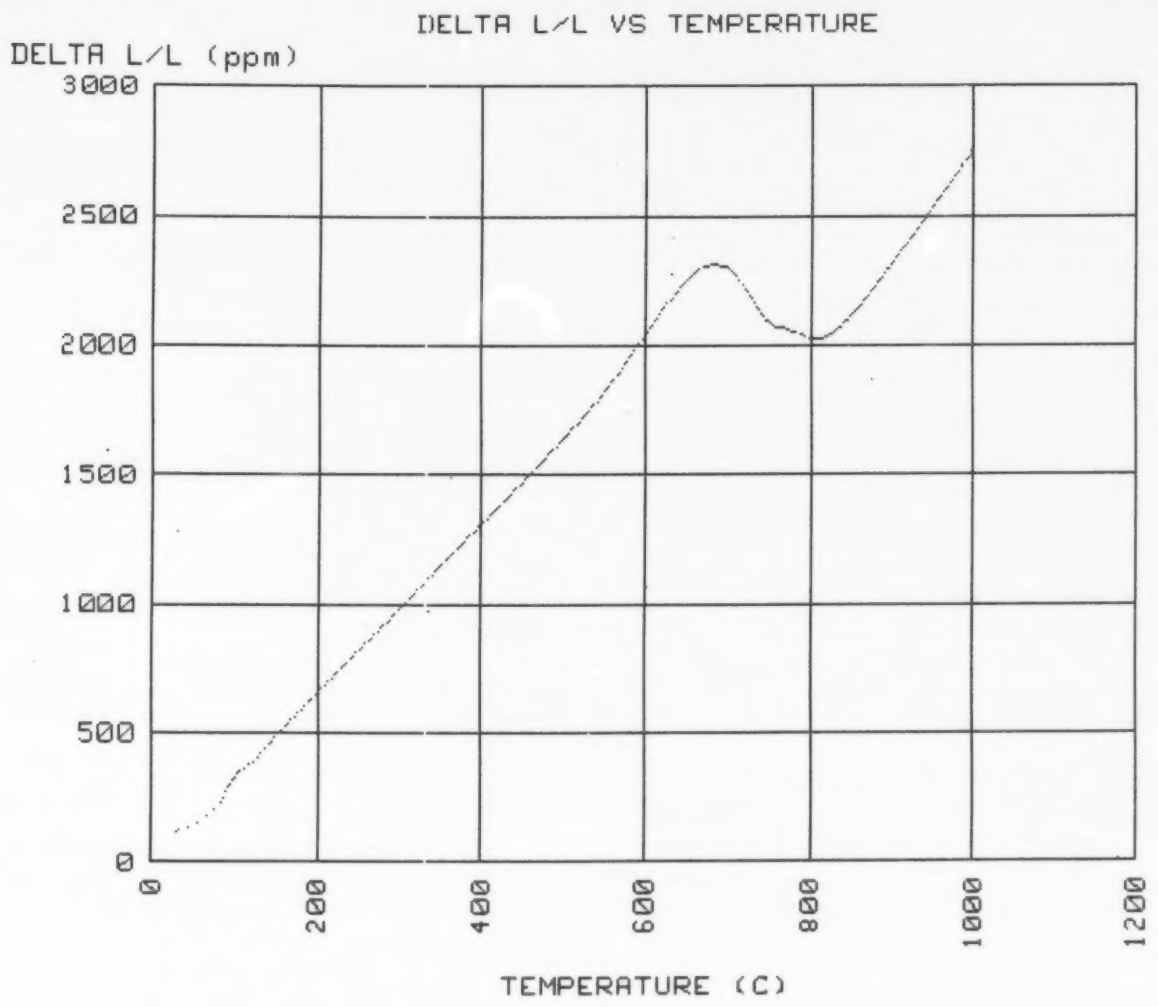
DATE AND TIME OF REPORT 04:02:10:46:34

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	640MAC
DATE OF RUN	03:02
RUN NUMBER	1
HP85 DATA FILE	640MAC
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.004
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	5.1 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	640MAC
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	DELTA L / L MEAS. ppm	CORRECTED ppm	&NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29225	28967	91	0.00
6	0	0	0	0	0.00
11	30	29226	28996	112	3.80
16	76	29268	29077	201	1.90
21	95	29359	29182	303	5.47
26	112	29402	29238	362	3.60
31	137	29460	29314	438	2.96
36	157	29522	29389	512	3.75
41	177	29575	29454	578	3.29
46	197	29632	29523	647	3.36
51	217	29687	29589	712	3.36
56	235	29737	29648	773	3.26
61	254	29790	29711	834	3.23
66	273	29841	29770	894	3.31
71	290	29893	29829	953	3.27
76	308	29941	29884	1009	3.17
81	326	29994	29943	1067	3.35
86	343	30046	30001	1124	3.34
91	360	30096	30055	1180	3.28
96	376	30147	30111	1235	3.26
101	393	30197	30165	1289	3.26
106	410	30247	30218	1343	3.24
111	426	30299	30273	1397	3.31
116	442	30350	30327	1450	3.35
121	458	30403	30382	1504	3.36
126	474	30453	30433	1557	3.34
131	490	30506	30487	1611	3.33
136	506	30558	30539	1663	3.26
141	522	30611	30593	1718	3.46
146	537	30670	30651	1774	3.65
151	552	30730	30710	1834	3.98

156	568	30795	30774	1899	4.09
161	584	30867	30844	1969	4.51
166	599	30941	30916	2039	4.67
171	615	31013	30986	2109	4.37
176	629	31082	31051	2175	4.45
181	645	31147	31113	2235	3.97
186	659	31197	31159	2282	3.23
191	674	31228	31186	2310	1.78
196	689	31233	31186	2310	.02
201	704	31216	31164	2286	-1.61
206	719	31158	31099	2223	-4.30
211	733	31089	31025	2151	-4.96
216	748	31037	30966	2093	-3.93
221	762	31024	30946	2070	-1.64
226	777	31017	30931	2056	-.94
231	791	31008	30915	2038	-1.22
236	806	31003	30901	2025	-.91
241	820	31024	30913	2037	.81
246	834	31062	30941	2067	2.08
251	849	31115	30985	2110	3.00
256	863	31175	31035	2160	3.51
261	877	31245	31095	2218	4.29
266	891	31318	31155	2279	4.23
271	905	31386	31213	2337	4.18
276	918	31458	31273	2397	4.60
281	932	31531	31332	2455	4.06
286	946	31605	31393	2516	4.40
291	960	31678	31453	2578	4.49
296	973	31756	31517	2640	4.64
301	987	31831	31578	2701	4.57
306	1001	31904	31634	1648	-72.72

Date:04:02:10:46:34 Sample:640MAC Data File:640MAC



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM 'CTE' VERSION 83/9/19 Glass & Ceramics Centre

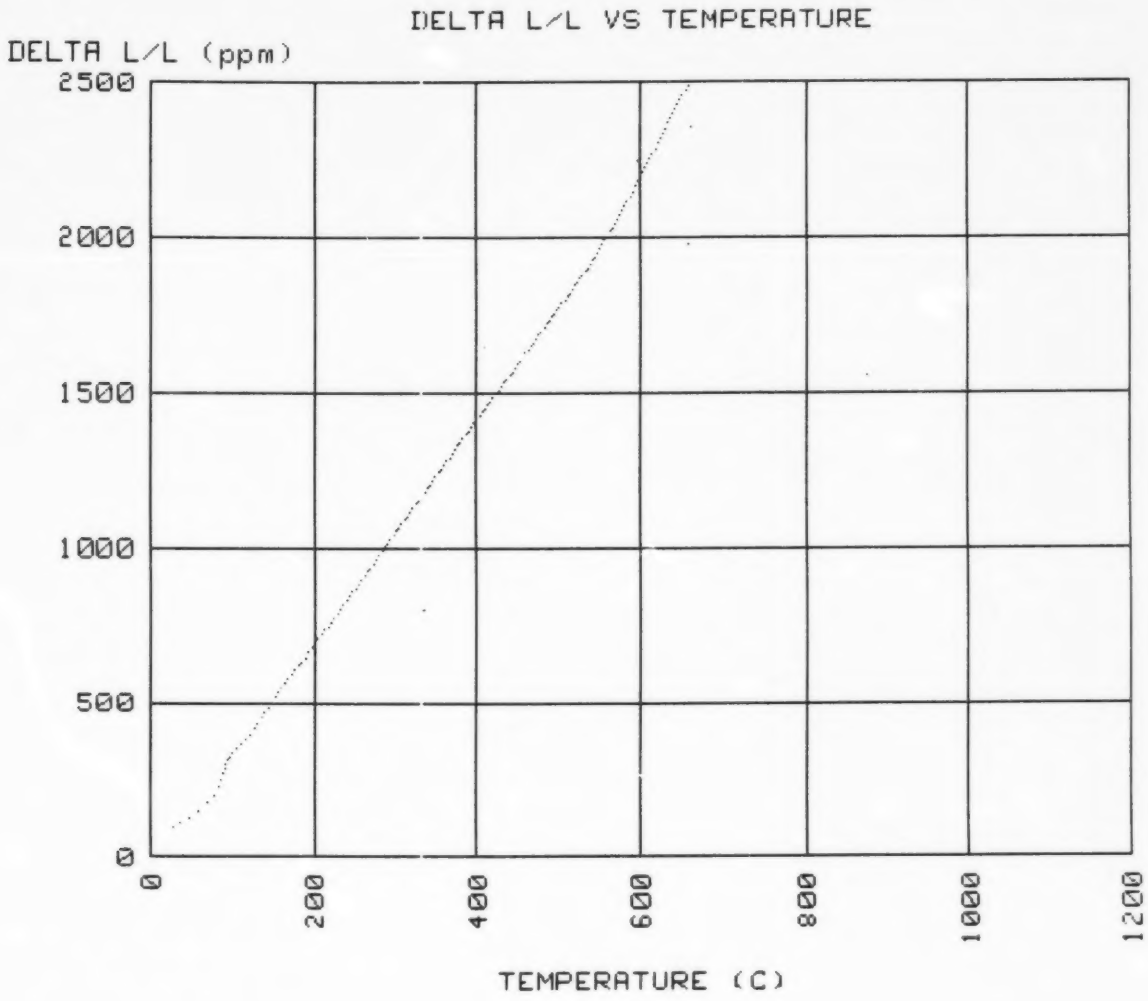
DATE AND TIME OF REPORT 04:02:17:01:58

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	641MAC
DATE OF RUN	04:02
RUN NUMBER	1
HP85 DATA FILE	641MAC
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.006
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	3.1 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	641MAC
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	DELTA L / L MEAS. ppm	DELTA L / L CORRECTED ppm	%NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29221	28964	70	0.00
6	0	0	0	0	0.00
11	29	29225	28994	96	3.32
16	77	29285	29095	200	2.14
21	93	29374	29196	300	6.28
26	112	29420	29256	364	3.50
31	137	29491	29344	450	3.41
36	156	29558	29424	530	4.14
41	177	29619	29499	604	3.55
46	197	29680	29571	675	3.55
51	217	29740	29641	747	3.68
56	236	29800	29711	817	3.65
61	254	29858	29779	884	3.61
66	273	29913	29842	948	3.53
71	290	29971	29908	1015	3.72
76	308	30030	29973	1078	3.55
81	326	30086	30036	1142	3.61
86	343	30145	30100	1205	3.62
91	360	30203	30163	1268	3.76
96	377	30260	30224	1330	3.72
101	394	30318	30286	1391	3.65
106	410	30375	30346	1451	3.60
111	427	30430	30404	1509	3.53
116	443	30485	30461	1568	3.61
121	459	30545	30523	1628	3.72
126	475	30600	30580	1686	3.65
131	491	30656	30637	1743	3.58
136	507	30713	30694	1800	3.58
141	522	30770	30751	1857	3.65
146	538	30830	30811	1915	3.69
151	554	30892	30872	1978	4.10

156	569	30960	30939	2046	4.30
161	585	31036	31013	2119	4.77
166	600	31115	31089	2196	5.07
171	615	31195	31167	2273	5.00
176	630	31278	31247	2352	5.21
181	645	31357	31322	2428	5.09
186	660	31432	31394	2360	-4.57
191	606	31147	31121	2227	2.47
196	621	31228	31199	2304	5.19
201	637	31310	31278	2384	5.12
206	652	31388	31352	2457	4.88
211	597	31099	31074	2251	3.79
216	612	31180	31153	2258	.47
221	627	31261	31230	2336	5.25
226	642	31343	31309	2414	5.09
231	657	31417	31379	1983	-28.90

Date:04:02:17:01:58 Sample:641MAC Data File:641MAC



ONTARIO RESEARCH FOUNDATION

THERMAL EXPANSION TEST AND ANALYSIS

PROGRAM 'CTE' VERSION 83/9/19 Glass & Ceramics Centre

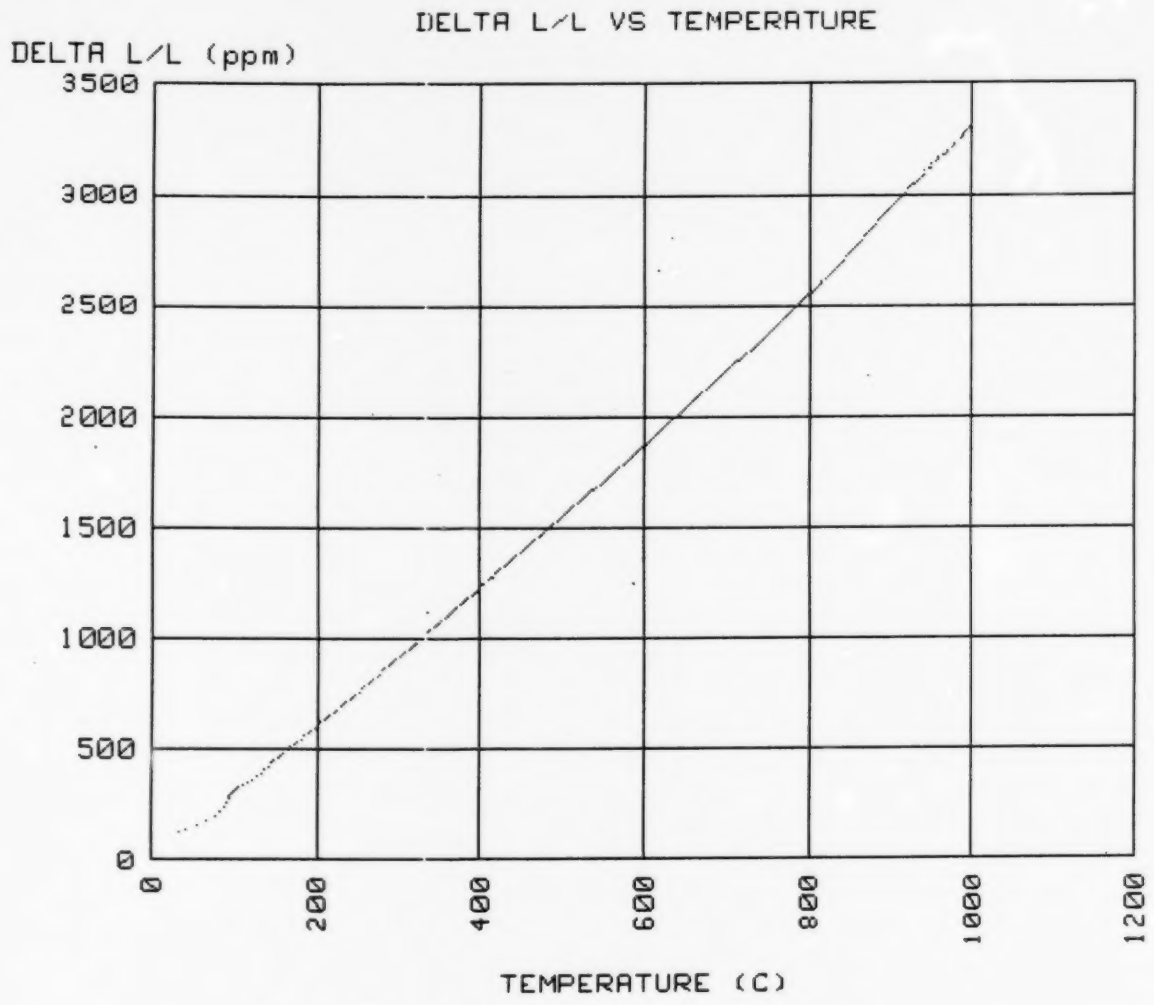
DATE AND TIME OF REPORT 03:02:11:15:32

FURNACE UNIT NUMBER	2
LVDT UNIT NUMBER	2
VALUE OF LVDT CALIBRATION COEFF.(V/in.)	2.9039
SAMPLE IDENTITY	STD/DPC
DATE OF RUN	02:02
RUN NUMBER	1
HP85 DATA FILE	STDDPC
HEATING RATE (Deg.C/min)	3
SAMPLE LENGTH (inches)	2.006
SOFTENING CHECK	DISABLED
DURATION OF RUN (hours)	5.1 hrs.
STANDARD MATERIAL?	NONE
HP9845 DATA FILE NAME	STDDPC
THERMOCOUPLE TYPE	S

POINT NO.	TEMP C	DELTA L / L MEAS. ppm	DELTA L / L CORRECTED ppm	&NORMALIZED (25C) ppm	INST.ALPHA ppm/C
1	0	29202	28945	94	0.00
6	0	0	0	0	0.00
11	0	0	0	0	0.00
16	78	29237	29047	197	2.53
21	96	29314	29138	285	5.03
26	111	29353	29189	340	3.51
31	137	29405	29259	407	2.58
36	156	29458	29325	474	3.48
41	177	29506	29386	534	2.95
46	197	29558	29449	597	3.06
51	216	29606	29507	656	3.14
56	235	29654	29565	715	3.06
61	254	29704	29624	773	3.13
66	272	29752	29680	830	3.11
71	290	29800	29736	886	3.11
76	308	29849	29792	941	3.18
81	325	29898	29847	996	3.11
86	342	29946	29900	1050	3.15
91	359	29994	29953	1103	3.13
96	376	30042	30006	1154	3.14
101	393	30090	30058	1207	3.16
106	409	30140	30111	1260	3.19
111	425	30188	30162	1312	3.19
116	442	30237	30214	1363	3.17
121	458	30287	30266	1414	3.19
126	474	30337	30317	1466	3.18
131	489	30387	30368	1516	3.24
136	505	30437	30418	1568	3.23
141	521	30486	30468	1618	3.19
146	536	30538	30519	1668	3.23
151	552	30588	30568	1717	3.18

156	567	30639	30618	1768	3.24
161	583	30692	30670	1819	3.30
166	598	30746	30721	1870	3.33
171	614	30799	30771	1920	3.30
176	629	30852	30821	1971	3.31
181	644	30904	30869	2020	3.32
186	659	30958	30920	2070	3.25
191	674	31013	30971	2120	3.34
196	689	31067	31019	2169	3.38
201	704	31120	31067	2218	3.25
206	718	31176	31118	2267	3.31
211	733	31233	31169	2317	3.44
216	747	31286	31216	2366	3.39
221	762	31345	31267	2416	3.46
226	776	31403	31318	2467	3.47
231	791	31460	31367	2516	3.53
236	805	31518	31417	2566	3.43
241	820	31576	31466	2617	3.54
246	834	31642	31522	2671	3.81
251	848	31707	31577	2727	3.91
256	862	31776	31636	2785	4.17
261	876	31843	31692	2843	4.01
266	890	31913	31752	2902	4.45
271	904	31978	31805	2954	3.66
276	917	32045	31861	3010	4.26
281	932	32105	31908	3059	3.40
286	945	32176	31965	3113	3.86
291	958	32239	32016	3164	3.96
296	973	32297	32059	3209	3.10
301	987	32361	32108	3259	3.61
306	999	32428	32161	1979	-101.22

Date:03:02:11:15:32 Sample:STD/DPC Data File:STDDPC



APPENDIX F

Permeability Data

ORF

Shell ID	Magna Helix (psi)	Gas Flow $cm^3/min.$	Adjusted Gas Flow $cm^3/min.$ (to 0.5 psi)
635TKM6	0.75	1,175	783
1000°C	0.68	1,200	882
635TKM7	0.70	1,175	839
1000°C	0.75	1,150	767
635TKM8	0.75	580	387
650°C	0.75	620	413
635TKM8	0.64	1,200	938
1000°C	0.64	1,200	938
636TKM6	0.75	600	400
650°C			
636TKM7	0.75	620	413
650°C	0.75	620	413
637	1.0	270	135
650°C	1.0	260	130
637	1.0	640	320
1000°C	1.0	590	295
638	1.0	790	395
650°C	1.0	770	385
638	1.0	1,250	625
1000°C	1.0	1,020	510
	1.0	910	455
640MAC	0.45	1,200	1,333
640TKM6	0.45	900	1,000
	0.30	1,200	2,000
641MAC	0.62	1,200	1,040
Standard DPC	0.575	1,200	1,050
(fired at ORF)	0.575	1,200	1,160
Standard DPC	0.5	950	950
(made & fired	0.5	890	890
at DPC)			

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